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LIGHTNING PROTECTION MEASURES FOR LOW-ALTITUDE TETHERED BALLOON SYSTEMS

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TECHNICAL REPORT

on

LIGHTNING PROTECTION MEASURES FOR LOW-ALTITUDE TETHERED BALLOON SYSTEMS

[Report No. A-4038(LP), Task No. 1]

by

P. E. Eggers, J. B. Brown, Jr.,
and R. G. Ollila

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91

FOREWORD

This study represents Subtask 1 under the task entitled "Special Studies in Low-Altitude Tethered Balloon Operations" (Task 1). This task was supported by the Defense Advanced Research Projects Agency (ARPA) of the Department of Defense and was monitored by the U. S. Army Missile Command, Redstone Arsenal, Alabama, under Contract No. DAAH01-72-0982. LTC G. H. Greenleaf, of the Tactical Technology Office of ARPA, was the technical monitor for this effort.

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DISCLAIMER

The views and conclusions contained in this report are those of the authors and should not necessarily be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U. S. Government.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

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ABSTRACT

The findings of a comprehensive review of information relating to state-of-the-art techniques for atmospheric electrical protection are reported for both ground-based (tall buildings, towers, power transmission lines) and airborne (aircraft, rockets) systems. An assessment has been made as to the applicability of this information to the protection of tethered balloons. Candidate techniques for the atmospheric electrical protection of balloons with conducting and nonconducting tethers are discussed. In addition, the results of investigative studies of the technical feasibility of air-ionization techniques for lightning protection are discussed.

INTRODUCTION

Atmospheric electrical phenomena are of interest to the military balloonist because of the threat of destruction of part or all of his balloon system by a multitude of electrical effects. As part of a task relating to low-altitude tethered balloon operations, the Defense Advanced Research Projects Agency (ARPA) requested the Tactical Technology Center of Battelle's Columbus Laboratories to investigate this threat by collecting and documenting information related to state-of-the-art techniques for atmospheric electrical protection of power transmission lines, tall buildings, aircraft, and rockets, and to assess this information in the light of applicability to tethered balloon technology. Further, the technical feasibility of air-ionization techniques for providing static discharge and/or lightning protection using radioactive emanations and laser beams was also to be investigated.

In this study, the lightning protection technology for ground-based and airborne systems has been surveyed through literature research and personal contacts with experts in the fields of lightning protection, simulation, and research-related fields of nuclear engineering and lasers. The technical information collected has been used as the basis for the analyses of plausible protection schemes for tethered balloon systems. In addition to existing lightning protection technology, several new concepts involving radioactive emanations and lasers were evaluated as to their applicability to the protection of tethered balloon systems. The development of the candidate lightning protection schemes (for tethered balloons) identified in this report has also made use of available reports and personal contacts in areas directly related to tethered balloon lightning protection. Techniques were developed for protecting balloons with conducting and nonconducting tethers from lightning.

SUMMARY

A comprehensive survey of the lightning protection technology for buildings, towers, power transmission lines, aircraft, and rockets has revealed a number of protection measures adaptable to low-altitude tethered balloon systems.

First, it appears that the concept of a "nonconducting" tether, to the extent that it prevents the balloon from experiencing ground potentials, is not practically attainable under all weather conditions. Hence, the tradeoff between nonconducting tethers and tethers with conductive elements (electrical power leads) should be reconsidered.

Second, the study revealed a number of measures that can be taken to minimize the frequency of triggering lightning. These measures include: the elimination of structural shapes which could otherwise lead to the local intensification of electric fields; the means for distributing and dissipating precipitation-static charges; and the minimization of the potential difference between the balloon and the surrounding atmospheric charge fields.

Third, the study has revealed protection schemes providing an addtitional measure of safety for the ground personnel. These measures include Faraday cages, grounding techniques, and the use of shunts between an elevated position on the tether and ground.

Fourth, the results of this study suggest that the protection of the balloon proper from lightning damage can be enhanced by providing a network of conductive paths on or near the skin of the balloon. Secondary shielding in

conjunction with surge-protection devices can further minimize the effects of nearby lightning discharges on the payload.

Finally, the study revealed several measures for reducing the susceptibility of tethers to lightning damage. These measures include: oil impregnation to minimize water absorption and retention in the interstices of the tether; coatings to reduce the effects of surface contaminants (e.g., salt-spray deposits) on tether resistance; and optional tether coverings (e.g., Teflon) offering greater resistance to surface contamination and streaking effects.

The study also involved a preliminary evaluation of the feasibility of two advanced concepts for lightning protection. The first concept, involving the use of radioisotope-enhanced lightning rods, appears to be ineffective since, under thundery conditions, naturally occurring rates of electrical discharge from lightning rods greatly exceeded those rates attainable using lightning rods involving biologically safe quantities of radioisotopes. A second approach was studied which involved lightning protection via the artificial creation of a preferred path for the lightning leader using lasers. The results of this preliminary evaluation suggest that it may be possible to create sufficient space-charge gradients with lasers to guide the path of a cloud-to-ground leader.

The report has been organized into five major sections:

<u>Technological Background</u> - Provides the reader with a frame of reference for the technical discussion and serves to acquaint him with the terminology used to describe atmospheric electrical phenomena and to increase his understanding of some of the fundamentals of clear weather and thunderstorm electrical activity.

<u>Atmospheric Electrical Protection</u> - Summarizes state-of-the-art techniques presently being used in the atmospheric electrical protection of ground-based and airborne systems.

<u>Applicability to Tethered Balloon Systems</u> - Provides a technical analysis and assessment of candidate lightning protection measures for balloon systems with conducting and nonconducting tethers.

<u>Technical Feasibility of Air Ionization for Static Discharge and/or Lightning Protection</u> - Analyzes two advanced lightning protection concepts: radioactive lightning rods and laser-generated lightning discharge channels.

<u>Conclusions and Recommendations</u>.

In addition, two appendices are provided: Appendix A briefly summarizes the findings of the NACA Subcommittee on Lightning Hazards to Aircraft concerning the frequency of lightning strikes as a function of altitude and ambient flight-level temperature. Appendix B presents a preliminary, simplified analysis for possible laser-channeling of the naturally occurring "stepped leaders" of the lightning discharge process.

TECHNOLOGICAL BACKGROUND

Clear-Weather Electrical Activity

Normally, the earth's surface is charged negatively, while the atmosphere, a poor conductor, contains a distributed net positive ionic space charge. Thus, a potential difference, increasing with height, exists between any level in the atmosphere and the earth's surface. The average potential difference between the 50-km (165,000-ft) level, near the base of the ionosphere and the surface is about 290 kV. The resulting fair-weather electric field is vertical and directed downward. In general, the potential gradient decreases with height, relatively rapidly below 3,000 m (10,000 ft), roughly exponentially at higher levels. However, below 3,000 m values above that at the surface may occur on occasion. The potential gradient varies locally, geographically, temporally, with changing weather conditions, and otherwise, the variability decreasing with altitude. At the earth's surface it has a usual value of about 100 V/m. A high value at 3,000 m is 45 V/m, at 5,000 m (16,000 ft), 30 V/m. Potential differences with respect to the earth's surface of over 300 kV have been measured at the 3,000 to 5,000-m altitudes.

To elaborate on this, consider the definition of potential gradient: potential charge per unit length, i.e., the potential difference between any two altitudes divided by the difference in altitudes. The potential difference (like Ohm's Law) between two points is equal to the product of the current flowing and the resistance between the two points. (Note: Ohm's Law cannot really be applied in this simple form to gases such as atmosphere, but for purposes of illustration we assume that it can.) The resistance (or conductivity) of a volume or column of air depends on the number and mobility of charged particles present in the column of air. Most charged particles present in fair weather are there as a direct or indirect result of cosmic rays bombarding the top of the atmosphere. Their collision with neutral air molecules forms ions and electrons which may in turn collide with other molecules, forming even more ions and electrons. Since the cosmic-ray intensity is attenuated by the air layer, the effect of cosmic rays decreases rapidly as we approach the earth's surface; fewer and fewer charged particles are therefore formed at the lower altitudes. An old controversy(1)* regarding potential gradient in the first several meters of atmosphere has essentially been reconciled by the thesis that some charged particles are formed near the surface of the earth by bombardment of emanations of radioactive material residing in the earth. This distribution of cosmic ray - air molecule interaction rate and the mobility and recombination rate of the resulting charged particles are therefore responsible for the fair-weather electric-field change with altitude.

That fair-weather potential gradients vary geographically is a result of at least two phenomena. The first is associated with charged-particle mobility. Ions formed in the air may group together to form "small" ions or attach themselves to large airborne particles to form "large" ions. These larger immobile particles contribute to a lesser degree to the conductivity of a unit volume of air than do the smaller sized ions. Airborne particulate matter, of course, varies geographically. The second effect is a result of geographical variations of cosmic-ray intensity. Over the ocean one would expect to find fewer charged particles than over land, but those present would probably be more mobile because of the presence of fewer large immobile particles. The resultant potential gradient is caused by a complex combination of all of these factors. Nevertheless, these geographical and altitude variations are small compared to the changes in the field that result from disturbed weather (thunderstorm weather).

Disturbed or Thunderstorm Atmospheric Conditions

A disturbed electric field occurs when an atmospheric process separates and/or moves charged particles in such a manner that a volume of the atmosphere becomes positively or negatively charged. One such

*References are given at the end of the report.

atmospheric process is the thunderstorm. Because the thunderstorm plays such an important role in atmospheric electrical effects to balloons, the reader should understand the general electrical configuration of what is called the "typical" thunderstorm. However, meteorologists will quickly point out that there is no such thing as a typical thunderstorm[2]. For example, the electrical nature of a thunderstorm topping out below 6,000 m (20,000 ft) is probably going to be different from one extending to 18,000 m (60,000 ft).

As a result of "The Thunderstorm Project", a thundercloud was found to be characterized by regions of strong upward or downward air currents[3]. These regions are known as cells. Whereas a thundercloud of small horizontal extent may have only one cell, an extensive thundercloud can have several cells in various stages of development, i.e., the cumulus stage, the mature stage, and the dissipating stage:

- Cumulus Stage: There is an updraft throughout the entire cell, the strongest updraft being near the top of the cell. The temperature inside the cell is everywhere higher than the temperature of the air surrounding the cloud at the corresponding level. No precipitation falls out of the base of the cloud at this stage.
- Mature Stage: Commences when the first rain beings to fall (see Figure 1). The following are characteristics of the mature stage:
  - Raindrops and ice particles are so large that they can no longer be supported by the upward air currents in the cloud.
  - Falling raindrops and ice particles drag the surrounding air along with them and so start a region of downdraft in part of the cell.
  - Downdrafts commence in the lower part of the cell and gradually extend to greater heights.
  - Updrafts persist in part of the cell, throughout the mature stage, the velocities being highest at high levels [as high as 30 m/sec (100 ft/sec)].
  - The cell is active electrically.
- Dissipating Stage: The downdrafts spread throughout the cell and gradually diminish in intensity. The rate of rainfall decreases to that of a steady shower.

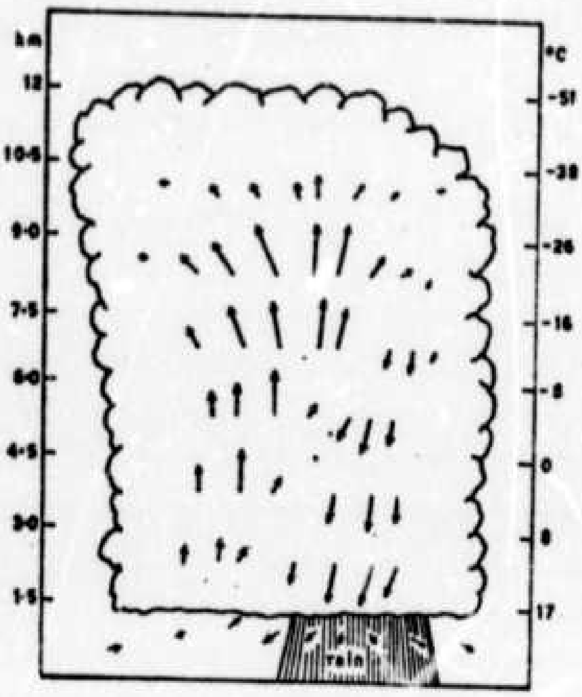

FIGURE 1. THUNDERCLOUD CELL

Arrows show wind direction; length of arrow is proportional to wind velocity. (From Reference 3.)

The Thunderstorm Electric Field

Clouds usually enhance potential-gradient values over those in clear air at the same levels. Some measured values for several (nonthunderstorm) types of clouds appear in Table 1.

Cumulonimbus clouds, in which thunderstorms occur, may extend from below 1,500 m (5,000 ft) to well above 12,000 m (40,000 ft) During storm development, a number of centers of charge concentration are produced. Generally, these are so distributed as to charge the upper portion of the cloud positively, the lower negatively. The negative charge concentration is estimated to be located just above the freezing level [typically 3,000 to 4,600 m (10,000 to 15,000 ft) above MSL in thunderstorm season], while the positive charge concentration is a few thousands of meters higher. In some cases, small centers of positive charge concentration are found below the negative charge concentration, in the lower part of the cloud. The horizontal separation distance of charge-center pairs has been reported as being typically from 1,500 to 5,000 m (5,000 to 16,000 ft). A great majority of lightning strokes occur between the negative and positive charge centers inside the cloud and between the negative center and the ground. Strokes can also occur between the positive center and the ground, and between unlike charge centers in adjacent cells. Near the end of a storm, after the main body of the cumulonimbus cloud has subsided and dissipated, the cirrus anvil may continue to give off discharges at relatively infrequent intervals over a protracted period of time.

The problem of measuring the intensity and direction of the electric field inside a thunderstorm is very difficult. The high liquid-water content affects the instrumentation, while the turbulence affects the attitude of the aircraft or balloon and hence the component of the field being measured. To make the problem even more difficult, a single thunderstorm may be composed of several cells, each in a different state of development. Consequently, the electrical structure of thunderstorms is not completely understood.

Some attempts to measure the potential gradient have, however, been attempted. A typical magnitude change of the potential gradient at the earth's surface for a close lightning discharge is about 5 kV/m. Potential gradients in thunderstorm clouds, however, are seldom vertical and appear to be of higher magnitude on the average near the freezing level. The results of a series of aircraft measurements indicate an average maximum potential gradient

TABLE 1. POTENTIAL GRADIENTS IN CLOUDS

Cloud Type	Cloud Height, m (ft)	Vertical Potential Gradient, V/m	Horizontal Potential Gradient, V/m	Remarks
<u>Stratiform</u>				
Stratus/stratocumulus	Below 1,500 (5,000)	310 (max)		Potential with respect to earth's surface at cloud top for nimbostratus cloud extending from 500 to 10,000 m (1,600 to 32,000 ft) theoretically calculated to be 400 kV and somewhat higher within the cloud
Altostratus	Near 3,000 (10,000)	840 (max)		
Cirrostratus	Near 5,500 (18,000)	680 (max)		
Nimbostratus	Approx. 1,000-3,000 (3,000-10,000) base to top	560 (avg); 1,860 (max)		
<u>Cumiliform</u>				
Cumulus (continental)	Approx. 1,500-5,000 (5,000-16,000) base to top	500 (mode); 7,000 (max)		
	Approx. 3,700-7,000 (12,000-23,000) base to top		960 (max, no precip.); 2,300 in snow	
Tropical cumulus (oceanic)		3,000 (max)		Lightning can occur without other thunderstorm manifestations
Trade-wind cumulus	Approx. 600-2,700 (2,000-9,000) base to top		<100 (avg)	
	Approx. 600-4,600 (600-15,000)		8,800 in rain	Single observation

for nine storms of 130 kV/m. One flight, in which the potential gradient averaged 70 kV/m over a distance of 13 km (42,000 ft) recorded two readings of 200 kV/m, and a third, just prior to the aircraft's suffering a lightning strike, of 340 kV/m. This is one of the highest values for a thunderstorm that has been reported. From measurements of charges carried by raindrops in a thunderstorm, it was calculated that the locally limited potential gradient at a drop surface is 1,200 kV/m, in the range of the dielectric breakdown strength of air, which is variously judged to be between 1,000 and 3,000 kV/m. Related theoretical calculations have indicated that within the cloud potential gradients of up to 2,000 kV/m and potentials of 10^7 kV can be produced.

Lightning Stroke Currents

Currents in lightning strokes usually consist of one or more successive component discharges, each of which has a high-magnitude peak of short duration (<10 μsec) followed in some component discharges by a continuing flow (tenths of seconds) of much lower magnitude. In strikes to high objects initiated by an upward streamer from the structure, the high peaks may not occur unless a charge center is contacted in the cloud. The average peak value of strokes initiated from clouds is about 20 kA, with peaks occasionally approaching 200 kA. The largest peak value ever recorded is 345 kA. Continuing currents seldom exceed 1 kA, and may be considerably less.

Lightning Discharges to Ground

It is well known that the fraction of lightning discharges in a thunderstorm that reach the ground is extremely variable. These changes occur (1) during the course of a single storm, (2) between individual storms, (3) with changes in local topography (flashes to ground more frequent in mountainous regions than over flat terrain), (4) with increasing geographical latitude[(4)], and (5) with diurnal variations. In the case of diurnal variations, the peak of the thundery activity generally occurs in the late afternoon and early evening hours. This diurnal cycle shows monthly and seasonal changes, even at a specific locality.

Cianos[(5)] has reported that there exist some general systematic variations in the diurnal cycle which depend on the character of the storms.

For example, the amplitude of the diurnal cycle is larger in semitropical zones than in temperate zones. Also, maximum thunderstorm activity occurs progressively later in the day as one moves from continental interiors to coastal regions.

Hence, there are a number of natural factors - geographical, meteorological, and diurnal - which influence the characteristics and frequency of cloud-to-ground lightning. These variables complicate the identification of typical lightning-discharge characteristics as well as the "preferred" lightning protection scheme. Also, cloud-to-ground lightning discharges represent only one of several modes of discharge which include intracloud, intercloud, and air flashes. The more frequently occurring intracloud discharges are discussed in the next section.

Intracloud Lightning Discharges

Generally, only about one-fourth of the lightning discharges reach the ground. Most of those discharges that do not reach the ground are of the intracloud type, i.e., dissipating entirely within a given cloud. Cloud-to-cloud and air discharges (between cloud and the surrounding air) are comparatively rare. According to Cianos' findings[6], intercloud discharges and discharges to earth have several similarities including the total duration of the discharge, the total charge involved, and the length of the discharge channel.

In contrast to cloud-to-ground discharges, the intracloud discharge[7] involves the propagation of a "leader" which bridges the gap between the main charge centers in a thundercloud, hence effecting a partial neutralization of the separated charge centers. This intracloud leader propagates at a comparatively steady rate and at a nearly uniform current. In the course of the leader propagation, it occasionally encounters a charge concentration of the opposite sign which results in a "return" streamer which recoils back along the channel preionized by the leader. (This recoil phenomenon is known as the K-effect.) Unlike the cloud-to-ground discharge, the intracloud discharge never involves an encounter with a charged surface of extent and conductivity comparable with that of the earth. Consequently, no rapid neutralization of charge can occur, which explains the fact that K-current peak surges are an order of magnitude less than those of the return strokes associated with cloud-to-ground discharges[6].

A comparison of the principal characteristics of intracloud discharges and cloud-to-ground discharges is presented in Table 2. Based on the parameters summarized in Table 2, the principal differences between the two forms of lightning occur in the peak current (during the return stroke or recoil) and the number of return strokes or K-effect recoils.

It should be noted that the cloud-to-ground lightning characteristics cited in Table 2 have been deduced mainly from ground observations and thus represent essentially the current/time and charge-transfer histories at the point where the discharge contacts the ground. As a result, the estimates of the peak current are higher than experienced by objects such as aircraft, tethered balloons, or rockets that may be struck while in free flight. Specifically, these types of airborne objects may become part of the cloud-to-ground or intracloud lightning discharge. However, the crest of the current surge in the return stroke (as measured at ground level) is not usually experienced more than 150 m (500 ft) above the earth[8]. As a result, a tethered balloon at altitudes greater than this, which becomes part of the discharge channel to earth, will not usually encounter a current as large as that occurring at ground level. The same reasoning holds for intracloud discharges, viz., the crest of the peak recoil current will be experienced in the vicinity of the encountered charge concentration of opposite sign, i.e., the origin of the K-effect recoil.

Far- and Near-Field Components of Lightning

In general, the fields produced by lightning consist of the far fields or radiated components and the near fields or static and induction components. Cianos[9] describes an analytical expression for the far- and near-field components for distances of approximately 3 km (10,000 ft), or greater, which consists of three terms as shown on page 14.

TABLE 2. COMPARISON OF LIGHTNING CHARACTERISTICS FOR CLOUD-TO-GROUND AND INTRACLOUD DISCHARGES

Parameter	Cloud-to-Ground Discharge		Intracloud Discharge	
	Typical	Maximum	Typical	Maximum
Duration of flash, sec	0.2	2	0.2	--
Peak current per return stroke (or K-current[a]), ka	10-20[b]	250[b]	2	--
Number of return strokes (or K-effect recoils[a])	2-4	26	30	--
Continuing current, kA	0.150	1.60	0.125	--
Charge in continuing current, coulombs	25	330	22.5	--

(a) Refer to intracloud discharges.

(b) As measured in vicinity of ground level.

$$E_t = \frac{1}{4\pi\varepsilon_0} \int_0^t \underbrace{\frac{M_t dt}{d^3}}_{\substack{\text{static}\\ \text{field}}} + \underbrace{\frac{M_t}{cd^2}}_{\substack{\text{induction}\\ \text{term}}} + \underbrace{\frac{(dM_t/dt)_t}{c^2 d}}_{\substack{\text{radiation}\\ \text{field}}} ,$$

where

$M_t = 2i_t \ell_t$

i_t = current at any instant t

ℓ_t = length of channel being energized by i_t

c = speed of light

d = distance from emanating source

E_t = radiated field at time t

ε_0 permittivity of free space.

Note that the decrease in the radiated field, E_t, is inversely proportional to the third, second, and first power of distance for the near field (static), induction term, and for the far field (radiating), respectively.

The fact that the lightning discharge involves a multiplicity of "sparks" gives rise to a complicated generation of radio signals which range from 10 kHz to 10^4 MHz.

The near-field component becomes important for distances of less than 15 km (48,000 ft). In particular, the peak magnetic fields are determined by the return stroke currents. Based on the results of calculations summarized by Cianos[9], the static magnetic fields at 10 m (33 ft) from flash range from 160 to 3200 A/m for peak currents of 10 to 200 kA. At 100 m (330 ft) from flash, the same range of peak currents gives rise to static magnetic fields of from 16 to 320 A/m. Finally, at 10 km (33,000 ft) from flash, the static magnetic fields for the same range of peak currents are only 0.02 to 0.38 A/m.

In contrast to the magnetic fields, the electric fields are determined by the interaction of the charge drawn from the thundercloud, the charge deposited along the leader, and the redistribution of charge during the various current stages of the flash. Calculations indicate that at 100 m (330 ft) from source, the electric field may be approximately 10 to 100 kV/m as compared with the fair-weather electric field of approximately 0.1 kV/m. Clearly, the electromagnetic fields produced by close lightning can be very large in comparison with the far-field components.

In summary, lightning characteristics depend on a number of geographical, topographical, meteorological, and diurnal factors and one must consider various forms of discharge - cloud-to-ground, intracloud, cloud to ground, and cloud to air. Furthermore, the critical lightning characteristics depend both on the distance from the ground and the distance from the lightning discharge. The implications of this variable character of lightning discharges on developing lightning protection systems are threefold:

(1) The most effective lightning protection system may be achieved only by customized approaches based on conditions prevalent at a specific balloon station.

(2) As will be discussed below, the lightning protection system will not simultaneously provide protection against direct lightning strikes, induced displacement currents, antenna currents, and static charge currents; some of the protective measures will minimize one or two of the above problem areas but may aggravate the problems in the remaining areas.

(3) Acknowledging that all of the lightning-related problems cannot be minimized simultaneously, and that other nonlightning-related systems constraints are in effect, then a rational approach to lightning protection requires specification of a priority list, ordering the various aspects in the mission as to their relative importance (e.g., operator safety may be rated first priority, on-board equipment second, balloon third, mission fourth, winch system fifth, etc.)

The following section enumerates the state of the art of lightning protection methods for tall buildings and towers, power transmission lines, aircraft, and rockets, and also provides a discussion of triggered lightning. At the completion of this state-of-the-art review, several important lightning models will be discussed. These models will provide a logical basis for extending the results for the above objects to the subject of this particular task, viz., tethered balloons.

ATMOSPHERIC ELECTRICAL PROTECTION

The purpose of this section is to summarize state-of-the-art techniques presently being used in the atmospheric electrical protection of power transmission lines, tall buildings and towers, aircraft, and rockets. The survey of successful static discharge and lightning protection schemes presently used provides a rational basis for evaluating their applicability to the protection of tethered balloon systems as well as estimates of the ion densities required for several novel concepts for balloon-system protection.

Before proceeding, the meaning of the two terms "lightning" and "electrostatic (or static) discharge" should be clarified. In fact, lightning is electrostatic discharge. The distinction usually made between the two is primarily one of magnitude. Lightning generally involves the discharge from a thunderstorm of a large amount of charge (and current) in a short time by a highly ionized, confined channel many kilometers long. Electrostatic discharges include the less violent point or corona discharges from an object to the immediate surrounding space (a few millimeters to a few meters).

Sensitivity of Systems

The previous section indicated the variety of factors influencing the character of lightning. This fact has important implications with respect to lightning protection, viz., that the assessment of lightning sensitivity can best be undertaken for a specific engineering system operating at a particular geographical location. For example, one aspect of the lightning hazard is to estimate the incidence of lightning strikes in the vicinity of the subject engineering system during the periods in which the system is exposed (i.e., during the period in which the balloon is aloft). However, this is only one aspect, and a thorough assessment of suitable lightning protection systems requires the specification of the lightning parameters (e.g., direct stroke, induced electromagnetic fields and current, peak return-stroke current, continuning current, radio interference) to which the system is most sensitive and the relative degree of sensitivity to each parameter. Without this specification of priorities, a lightning protection scheme may be designed which will protect against one type of hazard (e.g., the effects of a direct strike) but may introduce or amplify another type of problem (e.g., triggering lightning or inducing large current flows in equipment contained within the balloon). Clearly, if the balloon system were sensitive to only one parameter, e.g., peak currents encounterd during direct strike, then the design of the protection system and the estimate of the probability of system failure could be relatively straightforward. However, where a number of phenomenologically interdependent parameters are important, with respect to system sensitivity, then the design and evaluation of lightning protection systems becomes greatly complicated.

The cumulative findings of many researchers indicate that, in general, engineering equipment appears to be most sensitive to the peak current attained in the return stroke and the attendant magnetic forces which produce impulsive and often explosive effects. Cianos[10] and his co-workers have concluded that the magnitude of the peak return-stroke current is principally determined by charge distribution processes - especially those in the atmosphere adjacent to ground level during the period just prior to the contact between the leader and the earth.

Some equipment may be particularly sensitive to the rate of current rise and the accompanying voltages developed by coupling and inductive effects. Engineering equipment may also exhibit a sensitivity to the total charge transferred since it is indicative of the electrical erosion and heating that can occur - usually during the protected "continuing current" phase of the lightning flash. It is noteworthy that the total charge transferred (hence protracted current flow) and the peak currents are approximately independent and must be considered separately in developing lightning protection schemes.

The number of strokes and time intervals between strokes can also affect engineering equipment where capacitor charging by successive strokes is important. However, these effects are usually considered slight compared with those discussed above.

The importance of evaluating candidate lightning protection schemes in terms of all of the critical lightning parameters is illustrated in the following example. Consider two typically occurring forms of lightning discharge: one with and one without continuing currents; otherwise, both types of discharge are comparable in terms of their duration, the amount of charge passing, and the energy transferred. The difference is the way in which the charge is transmitted to earth. In the case of a discharge without continuing current, the charge passes in three short time intervals - on the order of a few milliseconds. In the case of a discharge with continuing current, over 90 percent of the charge is transferred in the continuing current. It is important to note that an object that is struck by lightning of either form may have a different sensitivity to each. Specifically, a given lightning arrestor may be able to sustain the impulsive currents of the three-stroke model (no continuing current) but might be severely damaged by the second form in which the long continuing current could cause excessive heating.

Current Methods for Atmospheric Electrical Protection of Selected Systems

Some of the current practices in atmospheric electrical protection for such systems as buildings and towers, power transmission lines, and aircraft and rockets are discussed below. In these discussions, the type(s) of atmospheric electrical protection which is being provided as well as the undesirable side effects, if any, will be indicated. It is important to distinguish between atmospheric electrical hazards which are naturally occurring in the environment and those hazards which are amplified by the mere presence of the system. For example, Pierce[11] has summarized several incidents whereby manmade devices were capable of artificially "triggering" lightning. As a result, candidate schemes for atmospheric electrical protection must be evaluated in terms of both their "influence" on lightning discharge (e.g., triggering) as well as their capability to protect the system from the effects of such a discharge.

The discussion of current methods for atmospheric electrical protection of selected systems will be followed by a review of lightning triggering effects which appear to have important implications with respect to tethered balloon systems.

Buildings and Towers

The principles of lightning protection of terrestrial structures has not changed appreciably since the time of Benjamin Franklin: intercept the lightning stroke before it can cause physical damage to the structure, carry the stroke currents to the ground (earth) along a controlled, low-resistance metallic path, and allow the energy of the stroke to dissipate in the resistance of the adjacent ground. Franklin is generally acknowledged as the originator (1753) of the "lightning rod" as a means to achieve the above objectives for lightning protection to structures. However, Franklin suggested that the lightning rod might serve a dual purpose, ". . . that pointed rods erected on buildings, and communicating with the moist earth, would either prevent a stroke, or, if not prevented, would conduct it, so that the building should suffer no damage"[12]. This dual nature of the lightning rod remained controversial until the early part of the twentieth century.

In view of our modern knowledge of the subject, a grounded conductor, when subjected to the electric field of a thundercloud, discharges a current into the atmosphere. The time variation of the magnitude of this point-discharge current has been frequently recorded. Its crest value is, as a first approximation, proportional to the magnitude of the electric gradient. In a typical electric field of 20 kV/m under a thundercloud, the current flowing through a vertical conductor 15 m (50 ft) high is about 5 μA. The charge dissipated by an average lightning flash is about 30 coulombs and, if the average rate of flashing is taken to be two flashes per minute, it follows that approximately 6,000 such lightning rods would be needed in a one-half-square-mile area to prevent one lightning flash. Hence, it must be concluded that, for practical purposes, the terrestrial lightning rod has only one purpose: to intercept a lightning discharge before it can strike a structure and then to discharge it harmlessly to earth.

A comprehensive investigation of lightning conductors by Golde[13] concludes that, as a first approximation, it is reasonable to visualize the normal natural lightning leader stroke as a self-propagating discharge which progresses towards the ground guided by the local field distribution in front of the leader tip but unaffected by any features on the ground until the critical breakdown strength of the remaining distance from the ground is reached. When this stage is reached, an upward streamer discharge is generally initiated and the leader stroke is diverted toward it. The principal exception to this "normal" discharge mode arises in the presence of a structure of great height (e.g., the Empire State Building, the lightning observatory on Mount San Salvatore, and the Apollo launch facility at Cape Kennedy). For such structures as these, the normal process of a downward leader stroke followed by an upward return stroke may be reversed in that the leader stroke is frequently initiated at the tip of the tall lightning conductor leading to an upward leader stroke followed by a pseudo-return stroke. Hence, present evidence indicates that the lightning rod or conductor serves to provide a "preferred path" for the lightning discharge and its influence to divert the discharge path is expressed in terms of its "attractive range". This characteristic range of lightning conductors will be discussed in greater detail below. In the discussion which follows, the protection methods for both the direct and indirect effects of lightning will be enumerated.

The protection of buildings and towers from the direct effects of lightning is based on the principles cited above. A practical rule of thumb, which is supported by both theory and practical experience, is that a tall object provides shielding against direct strikes for nearby and lower objects. This shielded volume is called the "cone of protection" (see Figure 2). Objects within this 1:1 cone of protection, as illustrated in Figure 2, are generally considered "protected". The term "protected" should be regarded in the statistical sense, however, since there does exist some slight risk of a weak lightning stroke striking an object within the 1:1 cone. The attractive range of an object (that distance within which essentially all strokes will strike the object in preference to other targets) increases with the ultimate stroke current amplitude. Hence, the effective cone of protection may be much greater than 1:1 for the high-energy and more dangerous strokes.

If a structure is not effectively protected from direct strokes by some tall adjacent structures, it is generally equipped with a heavy conductor laid along the exposed edges of the roof and/or lightning-rod terminals. If the structure has a metal frame, the lightning-rod terminals may be connected ("bonded") directly to that frame. If not, the terminals are connected to the encircling edge conductor. This conductor and the lightning-rod terminals are connected to ground either by heavy vertical conductors or by the framework of metal-frame buildings. According to the U. S. Lightning Protection Code[14], any conductors intended either to intercept the direct lightning stroke or to carry it to ground should weigh not less than 0.17 lb/ft (0.25-in.-diameter wire or equivalent). Copper is usually preferred for this purpose because of its resistance to corrosion.

Grounding of the structure is commonly achieved by means of rods driven in the ground or by buried copper conductors encircling the building and connected to the building framework or to the lightning conductors coming from the roof. It is important to note that peak lightning currents can be quite large (100 kA or more) and, hence, very large voltages will be developed across even small resistances (e.g., due to inadequate bonding of components in the lightning protection system). The Lightning Protection Code

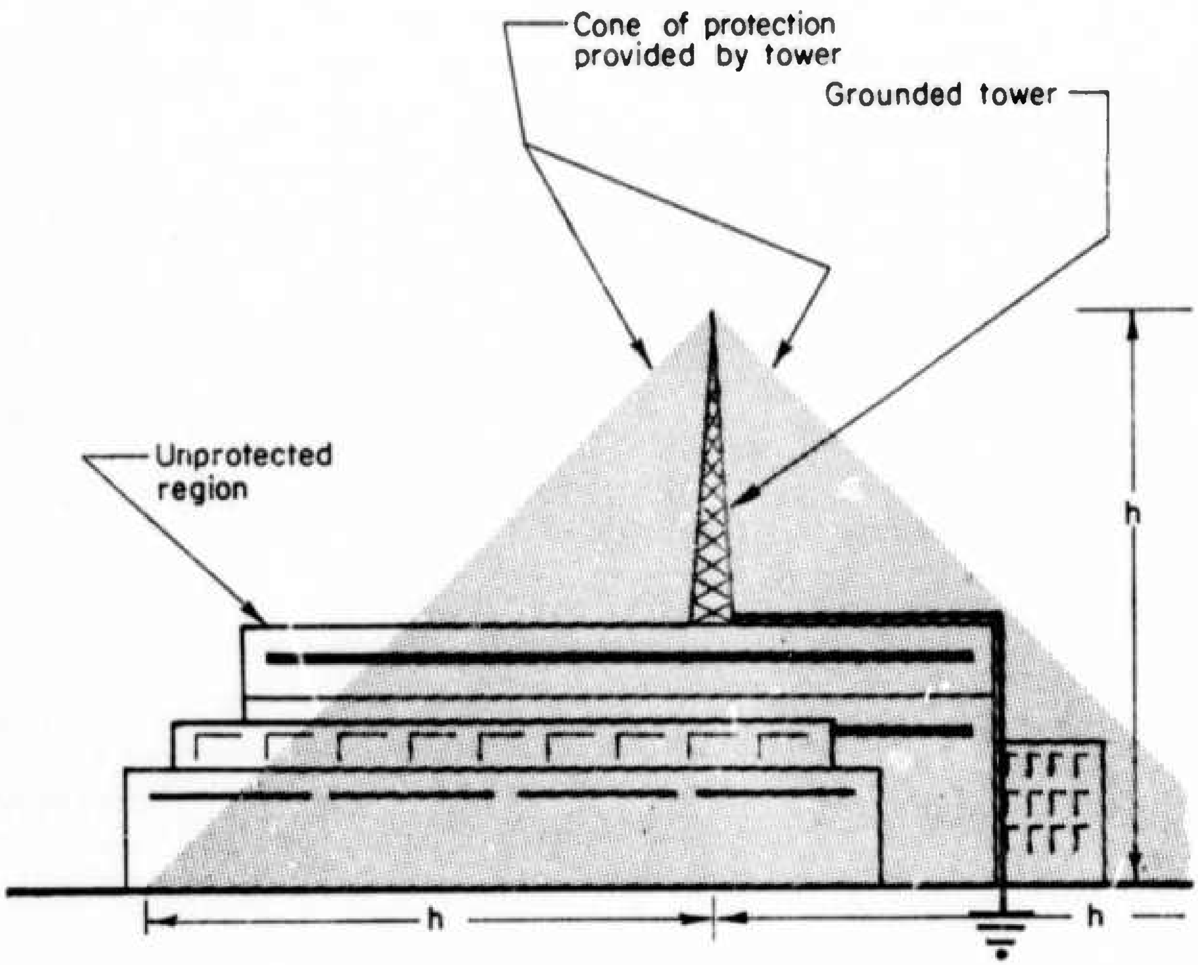

FIGURE 2. CONE-OF-PROTECTION CONCEPT FOR LIGHTNING SHIELDING BY TALL STRUCTURES OR RODS

recommends that the ground resistance be less than 10 ohms. In particular, Fisher[15] has analyzed the magnitude of the hazards due to the very large voltage gradients in the vicinity of the buried electrode. According to Fisher's estimates for a representative lightning stroke of 20,000 A incident on a lightning conductor connected to a buried, hemispherical ground rod (ground resistance of 16 ohms in soil with a bulk resistivity of 100 ohm-m), personnel and equipment would be endangered at radial distances of up to 4 to 6 m (13 to 20 ft) from the conductor.

A low grounding resistance is therefore required for several important reasons. First, apart from the inductive voltage drop which arises across a long down conductor, the ohmic voltage drop in the earth electrode determines the risk of side flashing. Second, the potential drop across the ground surface (as discussed above) is a direct function of the grounding resistance. These resulting voltages have caused many fatal accidents to human beings and animals.

Although a lightning-rod or -conductor system provides a safe path for the lightning discharge, it does not provide protection against the indirect effects, i.e., the effects induced in sensitive electronic equipment located in the vicinity of the discharge. For example, it has been found that a nearby lightning stroke can produce high voltages in electrical circuits, high enough to destroy the insulation on lights, motors, and control equipment. Although methods for protecting these types of equipment are well known and straightforward, those required for sophisticated electronic equipment are not, since surges of only 100 V may be damaging. These indirect effects, known as surge voltages, can be produced by changing electric fields associated with a lightning stroke, by changing magnetic fields, or by a high current flow through a nearby ground wire.

A review of the current literature[13-15] has revealed that the direct and indirect effects of lightning discharges to terrestrial structures and sensitive electronic equipment can be minimized by following the guidelines enumerated below:

(1) Try to divert the stroke away from the system, the farther the better.

(2) If the stroke cannot be diverted away completely, it must be carried to ground along a path where it does the least damage. This basically means providing a system of lightning rods as well as conductors to a low-resistance ground.

(3) Reduce the resistance along the current-carrying path as much as is feasible, particularly the ground resistance at the terminus of the lightning conductor.

(4) In buildings housing electronic equipment, establish a uniform potential ground plane over as much of the building as possible. In the case of concrete structures, all reinforcing steel members should be bonded together and connected to ground rods located around the perimeter of the building. All water pipes and utility conduits should be bonded to this ground system where they enter and at frequent intervals within the building.

(5) Where feasible, the bulding should be arranged to form a grounded metal enclosure (Faraday cage) since external magnetic and electric fields will not penetrate into such a enclosure.

(6) Power systems should be protected with commercially available lightning arrestors.

(7) In order to avoid "ground-loop" effects, ground systems that are isolated from building or power system grounds should not be used. The cases of all electronic equipment should be connected to the nearest building ground point, thus assuring the cases will not assume a high potential relative to the surrounding structure and so will not present an electrical hazard to those operating the equipment. Ground leads should be as short as possible and possess a minimum of resistance and inductance.

(8) All wiring between different locations should be carried in shielded cables with the shields grounded at both ends.

(9) Electronic equipment should be designed to withstand surge voltages. Surges can be carried into such equipment on input and output leads and on power supply leads, and steps should be taken to provide protective devices on these circuits.

(10) In cases where lightning protective measures (e.g., grounding both ends of cable shields) may increase system "noise" levels, protective devices such as Thyrectors* should be

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* General Electric Registered Trademark.

installed. These devices provide a high degree of electrical isolation between the various subsystems during normal system operation. However, a high voltage surge traveling on either ground system would see a low impedance connection between the two subsystems as a result of the Thyrector.

(11) For critical structures (such as explosive stores) it may be imperative to prevent a lightning current contacting any part of the structure surface. In such a case the conventional roof conductor system should be replaced by a system of catenary wires suspended from taller towers arranged around the structure and so designed as to exclude the possiblity of side flashing from the protective system to the building. This scheme is based on the same principle as the protection of an electrical transmission line by an overhead ground wire.

Power Transmission Lines

Lightning strikes to high-voltage power transmission lines have necessitated much research and expensive protective equipment for the electric utilities. Computers and other sophisticated electronic equipment are very sensitive to power fluctuations and/or induced electromagnetic effects caused by nearby lightning strikes and, therefore, are often inoperative when thunderstorms are in the area. In addition, strikes to power lines can interrupt power service for varying periods of time and backup power supplies, which are not likely to be shut down by lightning, are sometimes used when lightning activity is expected.

Since the chance of a conductor being struck by a lightning flash depends on its proximity to a particular charged cloud, it follows that any elevated structure is exposed to potential damage by lightning, and that the extensive high-voltage power transmission lines, which are strung between elevated towers, will be particularly vulnerable. Power transmission lines are given a measure of protection against direct strokes by means of one or more grounded wires which are strung parallel to and sufficiently high above the transmission wires to intercept lightning flashes (see Figure 3). The grounded wires are normally made of steel, which is less expensive than the copper or aluminum used for the transmission wires, and are electrically connected to the poles, which are also grounded so as to provide a low-resistance path to earth. Again, as emphasized in the previous section,

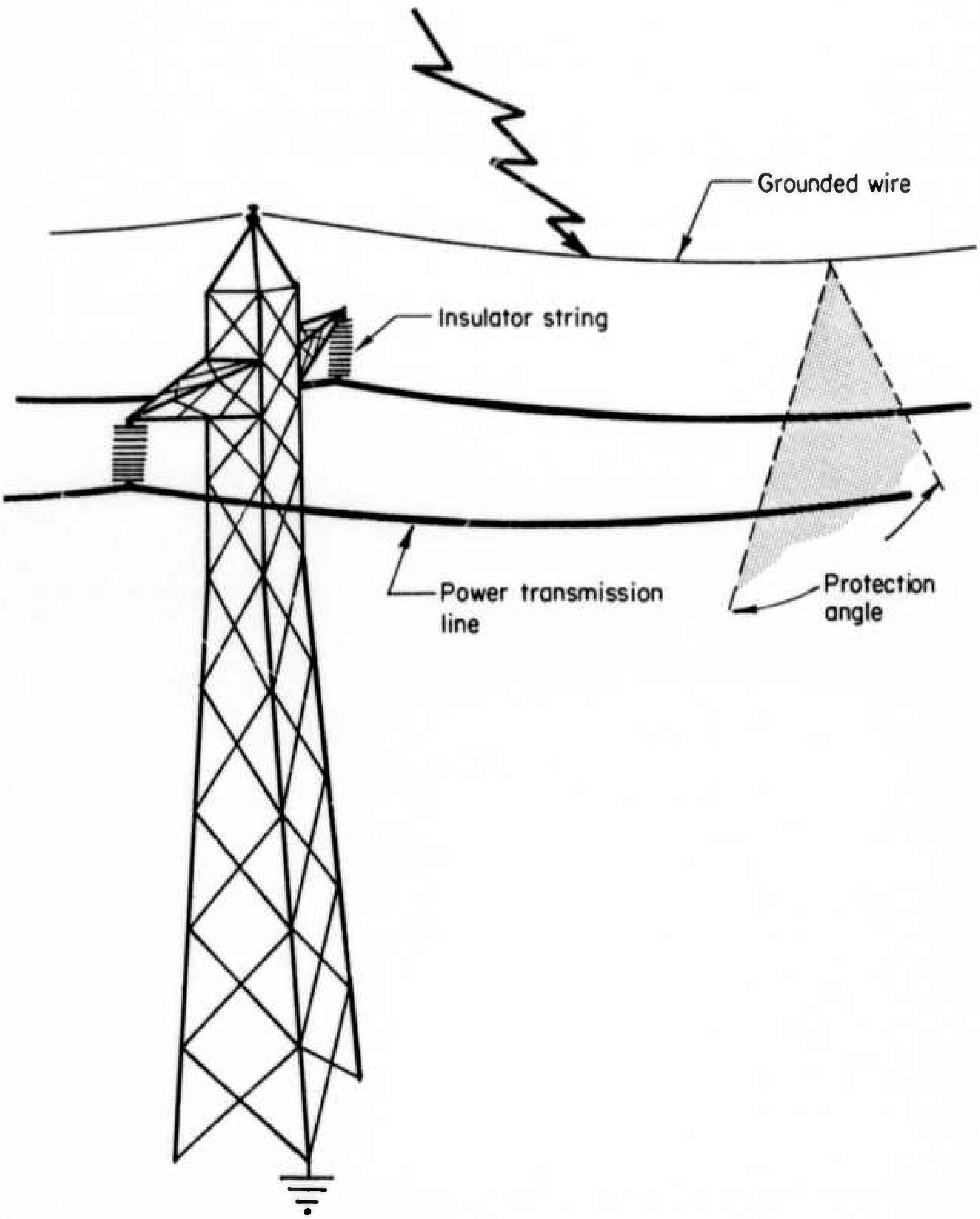

FIGURE 3. LIGHTNING PROTECTION SCHEME FOR POWER TRANSMISSION LINES

a high-resistance pole may result in side flashing from the strung grounded wires to the transmission wires when the ground wires are struck by lightning.

Induced surges with accompanying overvoltage on the power transmission lines can result from lightning discharges in the vicinity and hence, must also be considered in the protection scheme. Induced surges travel outward in both directions along the power transmission lines, and when they ultimately reach the ends of the line their voltage may be sufficiently high to damage transformers or other electrical appliances.

A synthetic material, thyrite, is commonly used to effectively divert high-voltage surges to ground and so protect the "end-of-line" equipment. Thyrite, whose basic constituent is silicon carbide, exhibits a drop in electrical resistance when the voltage across it increases. A surge diverter or lightning arrestor consists essentially of a block of thyrite mounted in series with a spark gap. It is connected between the power transmission line and the ground and the width of the spark gap is so chosen that spark-over does not occur at normal operating voltages. A high-voltage surge on the line causes the resistance of the thyrite to drop, and spark-over takes place, diverting the surge to the ground. Subsequently, when the voltage drops to its normal value the resistance of the thyrite rises again and the spark is quenched. On very-high-voltages lines, the short-circuiting arc can be kept going by the high voltage of the line after the lightning surge has passed. However, this problem can be solved by momentarily switching off the power supply by means of automatic trip switches at the power station.

The location of the ground-wire conductors (see Figure 3) is also of importance since failure of the ground wire to intercept the stroke nearly always results in flashover of the insulator string (i.e., a shielding failure). According to the lightning-stroke theory proposed by Wagner[16], the striking distance is equal to the stroke potential divided by the breakdown gradient per foot of rod-rod (i.e., parallel wire) gaps. The direction of leader propagation above the ground wire is influenced by the random field at its head, which produces the sudden changes in direction at each step, and by the "directive field" that controls its general direction. Young, et al.[17], have illustrated the effect of protective angle and the height of the ground wire on the number of shielding failures. The combined findings of a number of investigators[16] reveal that, for substantially perfect shielding, protective angles of 45, 30, and 12 degrees are required for ground-wire heights of 15 (50), 30 (100), and 51 m (170 ft), respectively.

Another approach to protection of power transmission lines is discussed by Rorden[18]. This protection scheme is used in regions where lightning incidence is relatively low and involves the use of high-speed relaying and high-speed automatic closing of 230-kV circuit breakers. The effectiveness of this scheme, i.e., the reclosing of the circuit breaker, depends to a large extent upon the deionization time of the arc.

In addition, there exists a second class of problems associated with high-voltage, power transmission lines involving the breakdown of or leakage around the insulator string. The significance of this particular class of problems with respect to tethered balloons will become apparent in subsequent discussions. For the present, it is noteworthy that the insulator string used in high-voltage systems has exhibited several modes of failure. One mode, which is known as "streaking", results from the discharge across the surface of the insulator string (often causing carbonization of the surface material) and provides a residual conductive path for subsequent leakage. A second and related failure mode involves the accumulation of a surface deposit which is inherently conductive (such as a salt-water deposit) and which complicates the maintenance of effective insulation strings in coastal regions. A partial solution to this problem has been the use of Teflon in place of some of the conventional insulator materials. Teflon has been found beneficial because of its resistance to streaking effects and its nonwetting characteristics, which inhibit the deposition of continuous leakage paths as well as promote self-cleaning during periods of natural rainfall. A second approach to this problem has been the use of special dielectric coatings such as silicone compounds. These coatings, which can be readily sprayed onto the insulators, act as a water repellent, thus restricting the formation of a continuous electrolytic film on the insulator surface. Also, any foreign material deposited on the insulator becomes engulfed by the compound thereby preventing the formation of a conductive path.

In summary, the major improvements for the protection of power transmission lines in recent years have resulted from the introduction of overhead ground wires, the use of surge protection devices (e.g., thyrite), and, in particular, the reduction of the tower footing resistance. In addition, special materials (Teflon) and coatings (silicone insulating compounds) have been used to minimize the problem of insulator breakdown due to surface leakage paths.

Aircraft and Rockets

In the early days of aircraft when airplanes were made of wood and cloth, the threat of lightning was not of much concern. This was probably because of the small number of aircraft flying, the relatively low altitudes involved, and the lack of formal documentation by the stricken pilot for the cases of actual lightning strikes. The later, all-metal aircraft (such as the DC-3) did not have much trouble with lightning as it simply went in one end of the plane and out the other. High-current vacuum-tube electronics were not greatly affected by the lightning-associated magnetic fields either. However, with the advent of low-current highly sensitive electronics, new dielectric structural materials, and sophisticated weaponry, lightning protection for modern aircraft has developed into a new science which is making available some new lightning protection techniques.

When modern aircraft are struck by lightning, they nearly always become part of the path the flash is taking. This is because the aircraft itself has little capacity to store electrical charge, as compared with the amount of charge that is known to actually flow in a lightning flash. Thus, in each incident flash there are normally two points where the lightning actually attaches itself to the aircraft: the "entry" and an "exit" point. Because of flash branching and the velocity of the aircraft relative to the fixed ionized path chosen by the lightning flash, there may be more than one entry or exit point on the aircraft, e.g., nose, tail section, or wing tip. At the points of incidence and emergence (attachment points), the flash usually leaves no more than a few pitted spots, each about a millimeter in diameter and spread over an area of less than a square meter.

The passage of lightning current through the airframe, between the flash attachment points, can be the cause of indirect effects as well. These result from magnetic-field interaction with aircraft electrical circuits and/or ohmic heating of resistive materials.

The principal direct and indirect effects of lightning on aircraft include the following:

(1) Puncture and pitting of metallic surfaces and disruption of composite nonmetallic materials; the important lightning parameters are the charge transfer and energy transferred.

(2) Mechanical damage to electrical bonds, conductors, protection strips and dielectric composites; the important lightning parameter is peak current.

(3) Damage to electrical and electronic systems from direct strikes to external electrical components and from induced voltages; the important lightning parameter is the current rise time.

(4) Fuel-vapor ignition by overheating or penetration of fuel-tank skins by arcing at electrical discontinuities and by strikes to tank vent outlets; the important lightning parameter is peak current.

All of these effects are a result of the currents that flow through the aircraft when it is struck by lightning.

Aircraft-Initiated Lightning. An important consideration in aircraft protection is that of the probability of stroke attachment which has been found to vary significantly over the surface of the aircraft. The TSS Standard No. 8-6 defines three zones on the surface of the aircraft according to the relative probability of stroke attachment. An abbreviated summary of this strike profile is given in Table 3. This "zonal" approach to lightning stroke analysis has led to the concept of aircraft initiation of lightning. For example, both analytic results and simulation testing have shown that an aircraft can trigger lightning when flying in a highly charged atmospheric environment. For such an environment, the electric-field intensification of the aircraft may become sufficiently high to initiate lightning which would otherwise not have occurred naturally. Furthermore, Shaeffer(19) has shown than an external source of charge is required to support an aircraft-initiated discharge.

It follows from the above that if an aircraft can initiate lightning, it becomes essential to identify how the exterior aircraft profile influences its propensity to initiate such a lightning discharge. As an example, the electric fields surrounding an F-4 and B-52 aircraft were determined(19) from the electrostatic integral field equations using an algorithm which included: actual aircraft geometry, an external cloud electric field, and a net charge on the aircraft. Capacitance of each specific aircraft was determined in order to estimate the charged vehicle potential and electrostatic field energy. The results of these analyses indicated that the nose pitot mast contributes the highest field intensification while the fuselage back has a low field intensification. These field-intensification factors, while high at the surface of the aircraft extremities, fall off rapidly as a function of distance from the vehicle. The rate of fall-off, however, is inversely proportional to

TABLE 3. SUMMARY OF LIGHTNING PROBABILITIES FOR THREE ZONES ON EXTERNAL SURFACE OF AIRCRAFT[20]

Zone	Stroke Probability	Surfaces Affected
1	High	• Within 0.5 m of any trailing edge, tail extremity or wing tip • Within 0.5 m of any sharp leading edge • Unprotected projections (e.g., nose, engine nacelles)
2	Moderate	• Surfaces which may be affected if strokes to Zone 1 are swept rearward • All fuselage surfaces not in Zone 1 are in this zone
3	Extremely remote	• Surfaces which do not fall in Zone 1 or 2 above

vehicle size, so that the region of electrical influence (beyond the vehicle proper) is proportional to vehicle size. The effect of a net charge on a vehicle is to increase the electric fields surrounding the vehicle as well as to increase the region of electrical influence. It is also noteworthy that the maximum charge that an aircraft can supply on the initiated streamer is just the maximum charge that the vehicle can hold. Thus, larger aircraft (or balloons) can support more streamer discharges since the maximum charge of a vehicle is proportional to the surface area.

<u>Mechanisms of Static Electrification</u>. The mechanisms for static charging of airborne vehicles include air friction and encounter with electrically charged water droplets and ice particles in flight. The results of Dawson's studies of the mechanisms of ice crystal electrification[21] indicate that aircraft charging is greatest in the presence of dry crystals of ice and snow whereas clouds undergo efficient charging in the presence of both phases, ice and water. In general, the aircraft will accumulate significant static electrical charge via one or more triboelectric charging processes[21] when operating in a precipitation environment[22]. By these mechanisms, the aircraft potential will be increased until it reaches a critical value and corona discharges will take place at high-gradient points on the aircraft exterior (i.e., the points of field intensification). These corona discharges not only increase the probability of aircraft-initiated lightning discharge but interfere with communication and navigation systems as well. This latter form of broad-band radio interference is known as precipitation static or "p-static".

<u>Problems With Nonconducting Surfaces</u>. The above problems of aircraft-initiated lightning and radio interference associated with precipitation static discharge are further complicated in regions where external surfaces of the vehicle are nonconducting. For example, physical damage to reinforced composite materials as a result of precipitation static discharge has long been a problem for aircraft operations[23]. This damage is in the form of burn-through spots or holes on honeycomb laminate skins which may be serious enough to weaken the structure or to provide a path for moisture to get into the core of the structure. Other forms of precipitation-static damage include charge accumulation on glass or plastic windshields with frequent discharge to imbedded heating element wires (for windshield defrosting purposes) causing the heater to burn out.

Another problem associated with nonconducting structures is that of static charge build-up during flight with subsequent discharge by personnel on the ground. Not only are personnel endangered, but the nonconductive regions can accumulate large charge concentrations and lead to subsequent streamer discharge and initiation of lightning, despite the geometry of the region. In other words, a nonconductive region does not have to have the shape of a pitot tube in order to develop critical levels of field intensification.

Problems With Transfer of Fuels. The generation of electrostatic charge by hydrocarbon liquids has long been recognized as a potential hazard by the petroleum industry. According to surveys taken during the period 1960-1969[24,25], there were 116 fires resulting from static electricity generated by the fuel during transfer to tank trucks. Over the same period, there were 33 incidents involving aircraft; 12 of which involved aviation gasoline, 15 with JP-4, and one with kerosene.

Specifically, whenever a hydrocarbon fuel liquid, such as a jet fuel liquid, flows with respect to another surface, a charge is generated in the liquid. Although the exact nature of the charging mechanism is not clearly understood, it is generally held that the charging is due to ionic impurities present in the hydrocarbon in parts-per-million (ppm) or parts-per-billion (ppb) quantities[26]. When the fuel is at rest, the impurities are absorbed at the walls of the container, with one part of the ionic material (e.g., the negative polarity) showing a rather strong attachment for either the fuel or the solid interface. Since the number of positive and negative charges is equal, there is no net charge on the fuel. However, when the fuel begins to flow, the charges associated with "less attracted" polarity (i.e., the positive charges) are swept along by the fuel while the opposite charges leak to the ground through the fuel containment vessel. Thus, in this case, the fuel acquires a net positive charge as it moves through the system.

When the charged fuel is transferred into a receiving tank, either of two mechanisms will occur: the charge will relax harmlessly to the walls of the tank, or, if the conductivity of the fuel is sufficiently low, the charge may accumulate giving rise to high potentials on the fuel surface. If the local potential exceeds the breakdown value for the vapor space, a discharge will occur. Whether or not the vapor will ignite depends on the composition of the vapor and the nature of the discharge. It should be noted that spark discharges from the fuel surface usually do not have sufficient energy to cause ignition. This is because the amount of energy released in a discharge from a fuel surface per unit length of time is limited by the electrical properties of the fuel. Also, due to the high resistivity of the fuel, only a limited area of the fuel surface can participate in the discharge. These factors tend to reduce the incendiary potential of spark discharges from a fuel surface.

Electrification of Rockets. Rockets and space vehicles can acquire electrical charge of various amounts from such processes as triboelectric charging from particulate matter; plasma processes in the ionosphere, radiation belts, and solar wind; photoelectric charging from high-energy radiation; and engine charging from various processes occurring in the combustion chambers of rocket engines. Of these charging processes, triboelectric charging and engine charging appear to be the predominant sources of detrimental vehicle charging from the standpoint of producing high vehicle potentials that lead to sparks, corona, and streamers[27].

Several significant findings by Nanevicz[27] include the fact that the Titan III launch vehicle appears to be connected to earth until it reaches an altitude of 200 m (650 ft) due to its highly conducting exhaust plume; and, experiments indicate that, in early stages of launch, the rocket motors charge the vehicle to potentials of hundreds of kilovolts. In view of the latter finding, corona discharges can be expected from prominent protrusions from the vehicle. In addition, precipitation charging of the frontal surfaces of the Titan were shown to occur as in the case of aircraft and were accompanied by streamer discharges on dielectric frontal surfaces.

Protective Measures for Aircraft and Rockets. Many different types of lightning protection techniques must be incorporated into a single aircraft in order to provide for safe operation in the lightning environment. These protective measures are generally developed for each individual aircraft component according to its specific application and location on the aircraft. Hence, a number of protective measures are currently used for aircraft and rockets in order to minimize the undesirable effects of lightning and precipitation static charging. These protective measures include schemes for: minimizing the incidence of lightning strikes; accommodating the stroke in the event that lightning incidence is not avoided; minimizing the structural damage, radio interference and biological hazards associated with precipitation static charging; and minimizing the hazards associated with charge accumulation during hydrocarbon fuel transfer and associated electrical discharge within the receiving tank. The applicability of these schemes with respect to tethered ballcons will be discussed in the ne t section of this report. It is noteworthy that the lightning and static-electricity problems encountered by aircraft are more closely related to the balloon system (with "nonconducting" tether) than any other of the engineering systems considered (i.e., buildings, towers, power transmission lines). Consequently, the following protective measures devised for aircraft are of particular significance to the operation of balloon systems under conditions of both clear and thundery weather. These protective measures are categorized below according to the objective of the protection scheme.

(1) Minimizing the Incidence of Lightning

- Selection of proper flight plan (see detailed discussion in Appendix A)
- Selective discharge of clouds above location of launch site by means of small rockets trailing conductive wires or other triggering means. This approach to minimizing the incidence of lightning is limited to "safe" periods of the order of seconds[28].
- Early detection of thunderstorms using highly sensitive detectors located at the extremities of the aircraft[29].
- Selective design of external features of the aircraft in order to avoid regions of field intensification leading to corona discharge and possible triggering of lightning. Avoid points (pitot masts) and small radii of curvature where possible; provide auxiliary path for charge redistribution on nonconducting surfaces.

(2) Accommodating Lightning Stroke

- Provide low-resistance path for lightning so as to minimize energy dissipation of electrical energy of stroke within the aircraft. One means of providing a low-resistance path for lightning is to insure that all metallic components are well bonded, i.e., are in good electrical contact. Where bonding is difficult provide peripheral transfer of lightning current so as to avoid unbonded region.

- Provide sufficient metal cross-sectional areas at any potential lightning attachment points in order to provide an adequately low resistance path for lightning discharge.
- Protect advanced composite structures (e.g., graphite/boron epoxy composites) or other nonconducting exterior surfaces using flame-sprayed aluminum or silver coatings, aluminum wire mesh, or thin foil aluminum strips. In the case of transparent glass canopies, increase the conductivity of the glass via selected formulations or the application of thin (transparent) metallic coatings.
- Protection of fuel systems is based on the nature of the lightning hazard. If fuel tanks are located such that the lightning channel can dwell or persist, such as the trailing edge of "pod" tanks, then the skin thickness should be designed to withstand the transfer of the heavy coulomb phase of the lightning discharge without causing penetration or hot spots which may result in fuel explosion.
- Protection of antenna systems using lightning arrestors in the antenna wiring circuit in order to protect ungrounded antenna systems. Also, proper electrical bonding should be provided for grounded antenna systems so that lightning current can transfer from the antenna to the aircraft metal structure without causing burning damage to the joint interface.
- Voltage-surge protectors and band-pass filters are installed in the aircraft to reduce the transient voltage effects. Reroute, shield, and twist wiring in order to reduce transient voltage effects to an acceptable level.
- Protection of logic-based avionic systems (digital transmitters/receivers) by incorporating protection measures into software subsystems, i.e., error checks.

(3) <u>Dissipation of Precipitation Charge</u>

- Provide means for passive or active[30,31] precipitation static discharge of aircraft in order to avoid charge accumulations sufficient to initiate streamer discharges. Such a precipitation static discharger has been evaluated by

Amason[32] who discusses discharger design, installation, and placement. In general, the dischargers are located on the trailing edges of the vehicle to effect point discharge into the slipstream. Since metal points tend to give off small sparks which interfere with radio communication, p-static dischargers are often fabricated using graphite-impregnated cotton wicks which, owing to their high resistance, give a uniform discharge without sparking.

- Provide means for discharging hovering aircraft (helicopters) using a "dropweight" grounding system in order to minimize biological hazards associated with potential of helicopter or its cargo relative to ground.

(4) Protection During Fuel Transfer

- Minimize danger of igniting vapor in region above liquid level in fuel tank by one of several "inerting" techniques: the use of nitrogen[33] to purge vapor space or the use of catalytic combustion techniques[34].
- Reduce electrostatic charge on fuel using[26]: A. O. Smith Static Charge Reducer; a 30-second relaxation tank; or the de Gaston Decharger.
- Reduce electrostatic charge on hydrocarbon fuels by the addition of the static dissipator additive, ASA-3 which has been used in aviation gasoline, JP-4, and aviation turbine fuel.
- Select fuels that are outside the flammable range during normal transfer conditions, e.g., kerosene and aviation fuel. Where JP fuel is used, it must be assumed that the fuel/air mixture in the tank is in the flammable range during fueling (see Figure 4).

Triggered Lightning

The incentive for man-triggered lightning is, of course, to discharge individual charge centers within cloud systems so as to reduce or eliminate the probability of lightning strikes occurring during specific time intervals and locations, e.g., during a rocket launch at a fixed launch site. Several techniques have been investigated that have successfully triggered lightning strikes:

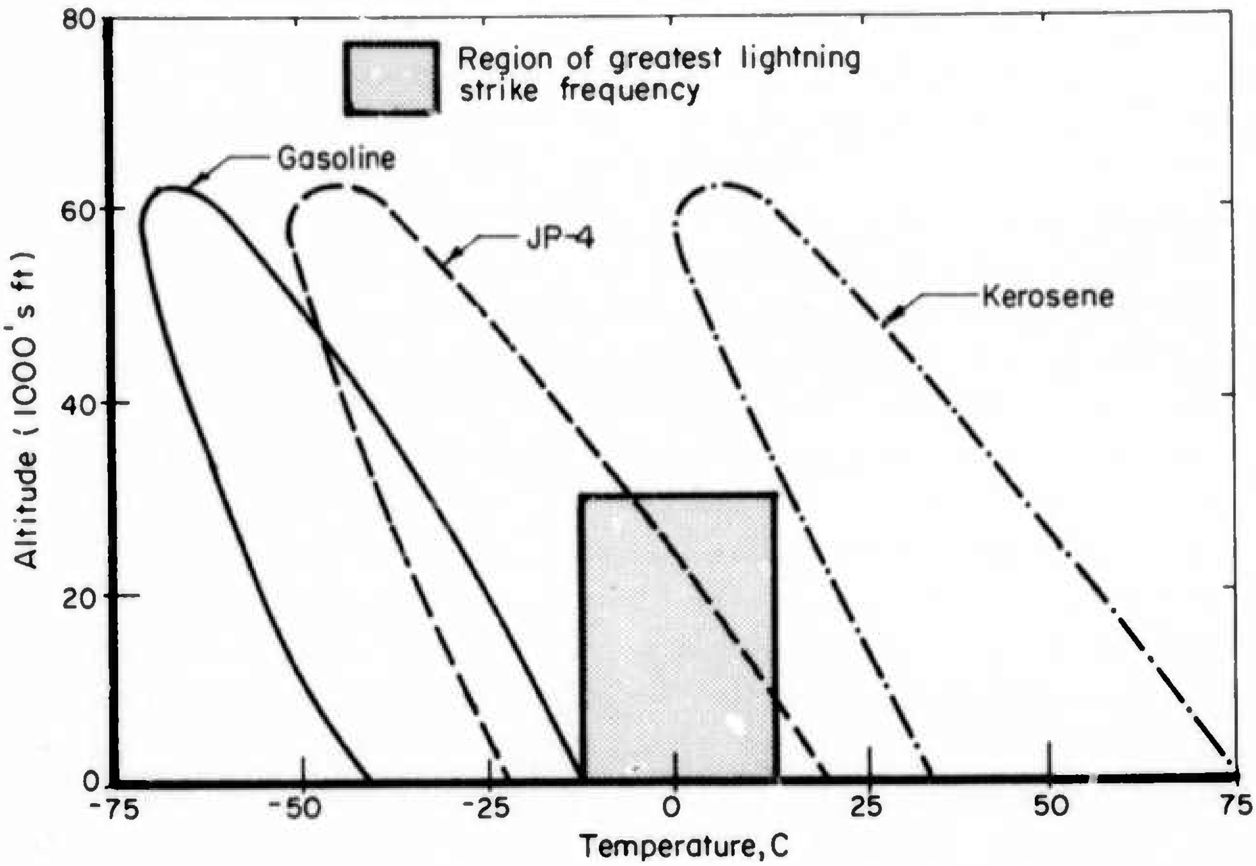

FIGURE 4. RANGE OF FLAMMABILITY FOR SELECTED AIRCRAFT FUELS AS A FUNCTION OF TEMPERATURE AND ALTITUDE

From Reference 35.

- Water plume arising from underwater explosion
- Rocket-launched wires
- Rockets themselves.

Rocket-Launched Wires. Sometime ago it occurred to Newman[36] and Brook[37] that it might be possible to initiate a lightning stroke at a particular place and time by rapidly introducing a wire into the electric field of a storm by the use of a rocket or some similar technique. It is interesting to note here that Newman, Brook, et al., emphasized the importance of introducing the wire "rapidly" into the electric field. Surprisingly, Brook found that if balloons were repeatedly flown on several kilometers of piano wire, into storms over the summit of Mt. Withington, New Mexico, no stroke ever hit the wire, even though discharges were occurring overhead at a rate of one or more per minute. Measurements showed that currents of several milliamperes flowed from the wire during the storm. Brook believed that the large amount of space charge thus released reduced the electric field near the wire and screened it from discharges. Some claim that it is through this mechanism that lightning rods probably prevent discharges under conditions of low wind velocity. However, Golde's research[13] argues against the effectiveness of this mechanism for practical lightning protection for buildings.

This hypothesis of being able to trigger lightning by the quick introduction of a wire into the electric field of a storm is strengthened by several chance observations of lightning strokes that appear to have been initiated accidentally by man. A lightning stroke apparently was triggered when a depth charge being tested by the U. S. Navy in Chesapeake Bay sent up a plume of water beneath a thunderstorm[38]. As was reported by Brook, et al., in the description of the strike, the first element of the four-element discharge began when the plume of water had risen to a height of 70 m (230 ft) in approximately 1 second. Additional evidence of this "transient" effect was demonstrated by Brook with experiments involving a Van de Graaff generator. In essence, the experiments showed that a grounded steel wire (0.01-in. diameter), when placed rigidly between the Van de Graaff electrode and ground, would suppress any sparks from the electrode. However, when the grounded wire was introduced rapidly into the electric field, a spark would invariably jump from the high-voltage electrode to the wire. Brook concluded that the chances of triggering a lightning stroke are good if one rapidly projects a fine wire up under a thunderstorm.

Robb[39] verified Brook's findings by firing wire-pulling rockets to altitudes of about 500 m (1,600 ft) when the over-water storm field was about 20 kV/m. Seventeen strokes were triggered by Robb out of 26 attempts[40].

The Apollo 12 vehicle triggered lightning strokes at 2,100 m (7,000 ft) when the surface field was about 3,500 V/m[39]. Postflight analysis of data obtained at Cape Kennedy and Patrick Air Force Base indicated two or three natural intra- or inter-cloud lightning events had occurred within 30 km (18 miles) of the Cape in the 25-minute period prior to launch.

Conceptual Framework for Triggering Natural Lightning. One approach to conceptualizing the triggering of natural lightning has been suggested by Pierce[11] and appears to agree closely with presently available data on lightning strikes to tall structures, aircraft, rockets, and rockets trailing conducting wires. The triggering concept is simply that in order to trigger lightning, the product of two components (the length or height of the object, L, and the ambient electric field E_a) must be on the order of 10^6 V. This product is referred to as the voltage discontinuity, V_D, and has been repeatedly found to be approximately 10^6 or larger in a wide range of lightning-strike incidents. As shown in Figure 5, a balloon operating at typical altitudes 2,000 m (6,500 ft) will satisfy the voltage discontinuity threshold requirements of 10^6 V with only a 1,000 V/m ambient electric field, i.e., at the low end of the range for typical thunderstorm environments (1 to 20 kV/m). This voltage discontinuity is thought to result in sufficient field intensification to allow electrical breakdown at the extreme point of discontinuity (see Figure 5) with the resulting streamer bridging the gap between the balloon and the charge concentrations in the nearby clouds.

The only exceptions to this discontinuity theory involve aircraft with relatively small lengths (by comparison with tall buildings or tethered balloons), in which case the observed high levels of static charge accumulations are thought to increase the effective "field intensity" to the point where the total discontinuity approaches the required threshold, i.e., approximately 10^6 V. Also, Pierce claims that it makes no difference whether the cable is nonconducting or conducting since the relaxation times involved are usually sufficiently long to permit charge distributions to effect the type of equipotential perturbations shown in Figure 5. Also, in contrast to Brook's[41] "transient" concept of artificial initiation of lightning discharges, Pierce's concept does not require that the voltage discontinuity be introduced within any time interval.

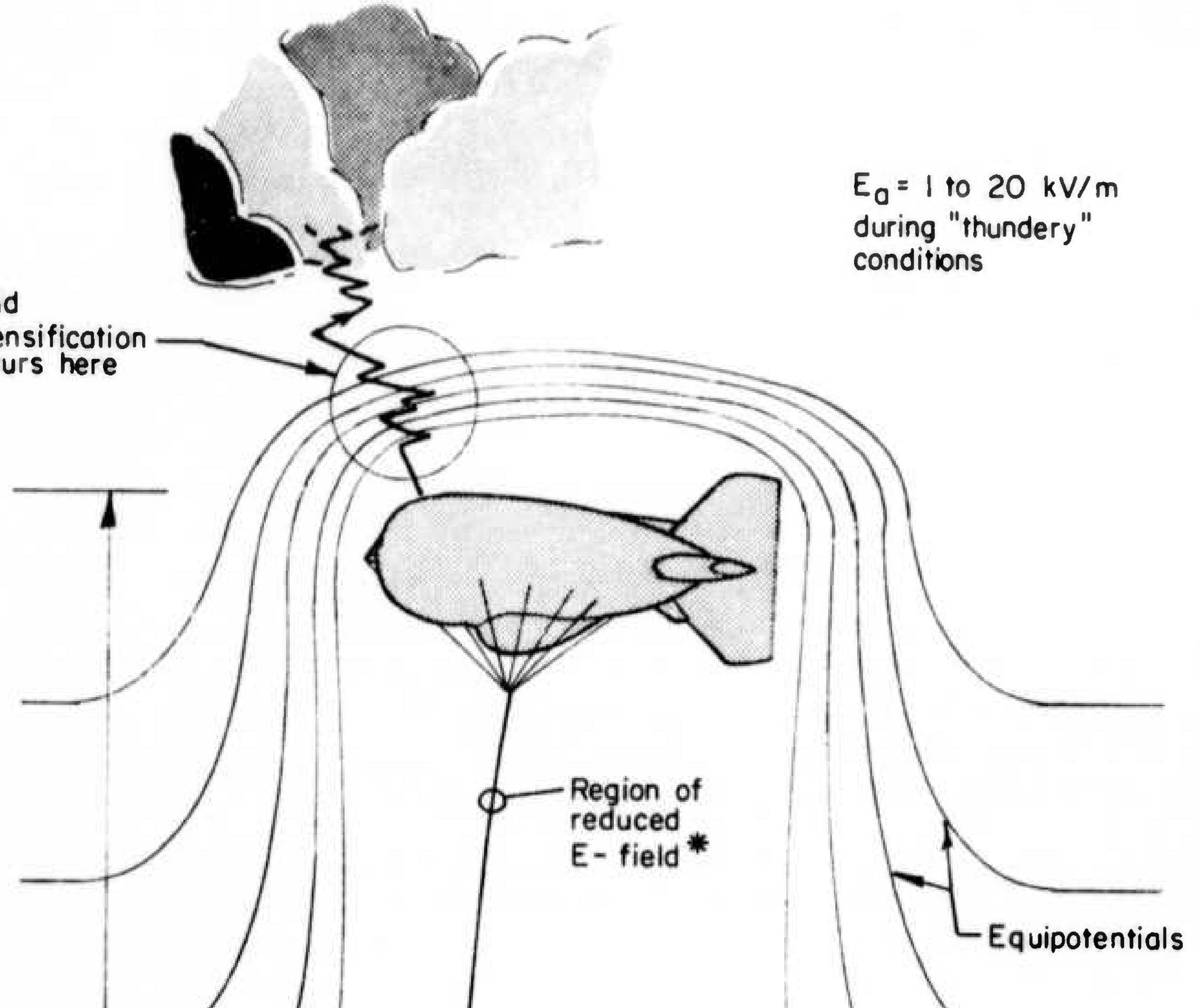

FIGURE 5. SKETCH OF BALLOON ENVIRONMENT ILLUSTRATING VOLTAGE DISCONTINUITY CONCEPT FOR TRIGGERED LIGHTNING

APPLICABILITY TO TETHERED BALLOON SYSTEMS

The preceding discussion of atmospheric electrical phenomena and the enumeration of related protection schemes for earth and airborne engineering systems provide an important "input" to the subsequent analysis and assessment of protection schemes suitable for tethered balloon systems (see Figure 6). The schematic diagram in Figure 6 reveals several important aspects of the technical analysis and assessment task: a multiplicity of protection measures are currently used for nonballoon systems (buildings, towers, aircraft, etc.); the available protection schemes must be considered in view of their systemic nature, i.e., they may have favorable or unfavorable side effects; the selection of the optimum protection scheme will require considerations of geographical, topographical, and meteorological conditions unique to a given location; and, the selection of a protection scheme presupposes an assumed set of criteria and priorities with respect to the tethered balloon mission (a sample list of criteria/priorities appears in Figure 6). Hence, the interactive nature of the protection measures and their dependence on local conditions requires that the candidate schemes be evaluated from a total systems point of view.

One systematic approach to the consideration of alternative protection measures is illustrated in Table 4. The purpose of this decisionmaking aid is to provide a methodical and rational evaluation of each alternative protection measure in view of the more important aspects of the overall system. This decision tool will be used to supplement the following discussion of candidate protection measures.

Protective Measures for Balloons With Conducting Tethers

Laboratory studies by Brook[41] and field experiments by Vonnegut and Moore[42] have indicated that grounded, fine wires (0.01 to 0.015 in. in diameter) positioned in high electric fields (occurring in the laboratory or naturally) undergo discharge processes which increase localized space charge and reduce the electric field. The apparent effect is one of reducing or eliminating arc or lightning discharges to the wire. For example, Vonnegut and Moore have flown balloons on several kilometers of piano wire directly into storms over the summit of Mt. Withington, New Mexico, with no stroke hitting the wire directly.

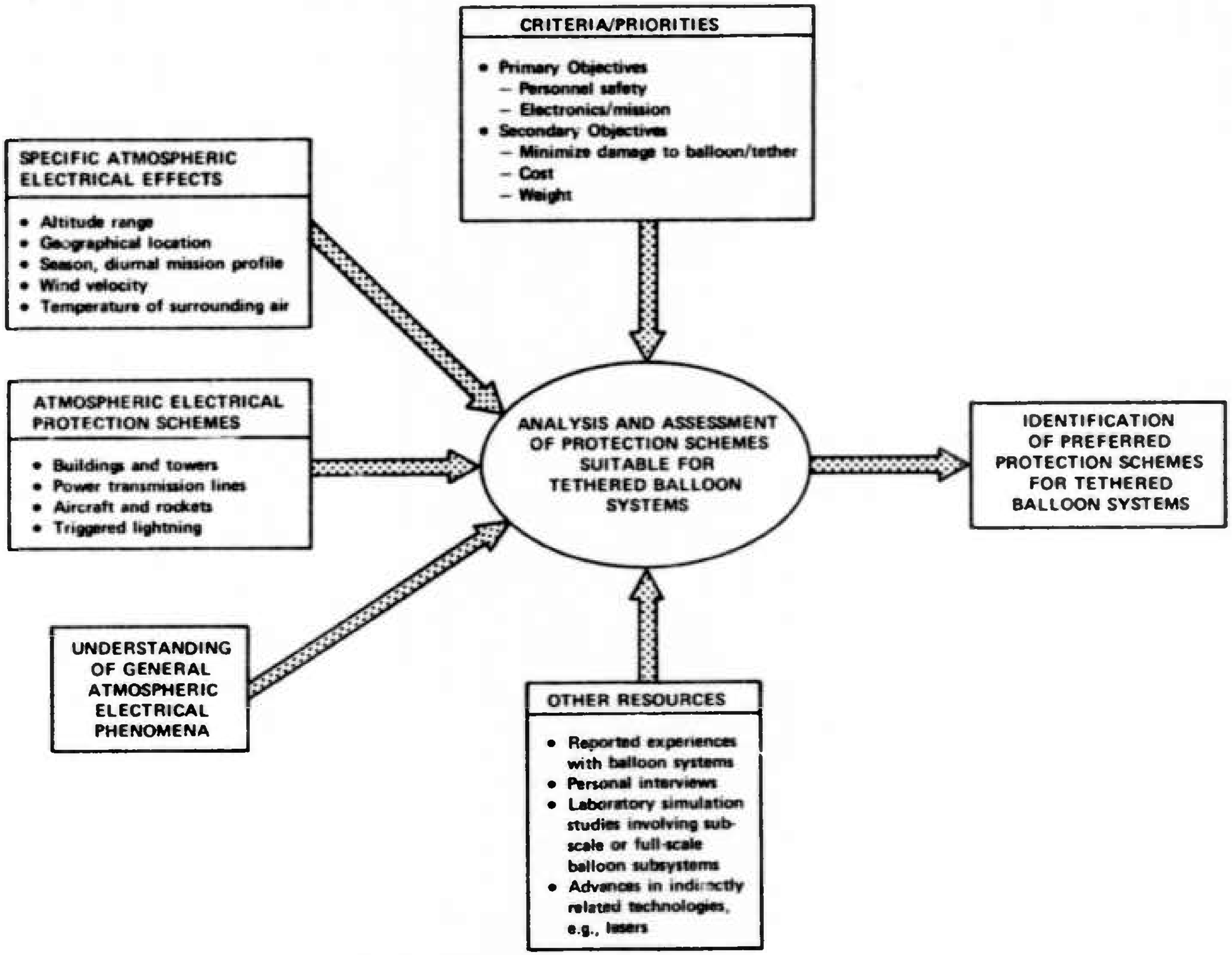

FIGURE 6. SCHEMATIC DIAGRAM OF ANALYSIS, ASSESSMENT AND IDENTIFICATION OF PROTECTION SCHEMES FOR TETHERED BALLOON SYSTEMS

TABLE 4. CANDIDATE PROTECTION MEASURES FOR TETHERED BALLOON SYSTEMS

Candidate Protection Measures	Effect[a] of Candidate Measure on: Safety of Personnel	Protection of Electronics From Damage	Protection of Electronics From Temporary Interference	Protection of Tether	Protection of Balloon	Protection of Ground Equipment	Duration of Mission	Operation Under All Weather Conditions
For Balloons With Conducting Tethers								
Balloon Protection								
Lightning Rods	0	+	-	0	+	0	0	+
Catenary Wires	0	+	-	0	+	0	0	+
Conductive Skin	0	0	-	0	+	0	0	+
Early Warning System	+	+	0	+	+	+	-	-
Personnel Protection								
Faraday Cages	+	0	0	0	0	+	+	+
Ground Planes	+	0	0	0	0	+	+	+
Electronic Equipment Protection	0	+	+	-	0	+	+	+
For Balloons With Nonconducting Tethers								
Modified Tether Designs								
Oil Impregnation of Tether	+	+	0	+	+	0	+	+
Silicone Coating of Tether Covering	+	+	0	+	+	0	+	+
Teflon Outer Covering	+	+	0	+	+	0	+	+
High-Conductivity Shunt to Ground	+	0	0	+	0	+	+	+
Balloon Protection								
Catenary Wires	0	+	-	0	+	0	0	+
Lightning Rods	0	+	-	0	+	0	0	+
Conductive Skin	0	0	-	0	+	0	0	+
Early Warning System	+	+	0	+	+	+	-	-
Personnel Protection	+	0	0	0	0	+	+	+
Electronic Equipment Protection	0	+	+	0	0	+	+	+
Protection During Fueling	+	+	+	+	+	0	+	+
Protection via Flight Plan	+	+	+	+	+	+	-	-

(a) + = positive or desirable effect; 0 = no effect; - = negative undesirable effect.

However, Vonnegut suggests that this may not be the case with any future conducting-tether experiments with balloons in thunderstorms. The popular explanation for the previous flights of conducting wires without lightning incidence is that the large amount of space charge released by the wire tether reduces the electric field near the wire and screens it from lightning discharges. At wind speeds sufficiently low that the space charge is not blown away, this mode of lightning protection might have merit. However, the practicality of this protection measure is further complicated by the fact that in a typical thunderstorm many cells or charged-cloud domains exist. Hence, the space charge released by the wire tether, altough reducing the electric field between the wire and one cell may, indeed, increase the field between the wire and another cell. In effect, it is very difficult, if not impossible, to truly predict and control the electric fields that may exist between a conducting tether and the dynamic environment imposed by changing thunderstorm cells (changing in position, charge level, and charge sign).

In addition to the uncertainty posed by environmental conditions and the requirement for low wind velocity, the conducting tether is limited to very small diameters (0.01 to 0.03 in.) or else it must have fine surface points in order to initiate the desired corona discharge processes which lead to significant increases in space charge surrounding the tether. Also, a conducting tether is susceptible to displacement and antenna currents which may subject the balloon to undesirable effects in the vent of a nearby lightning discharge. First, in the event of a nearby lightning strike, the conducting balloon tether is subjected to large displacement or readjustment currents. Specifically, charges induced in a tether from a nearby dipole (negative cloud base and positive ground under cloud) turn into current surges when cloud-ground dipoles are temporarily destroyed via lightning discharge. An example of the magnitude of displacement currents was revealed by Moore[43], who has flown conducting wires (0.01 to 0.015-in. diameter) across a canyon via a balloon lift procedure. In this experiment, the lower end of the conducting wire was isolated from ground by 10 m (33 ft) of nylon rope. Moore reported that about forty-five 10-m-long sparks discharged between the end of the conducting tether and the ground whenever a lightning flash was noted at a distance of about 1 km (0.6 mile) from the tether.

Second, in the event of either nearby or distant lightning strikes, the conducting balloon tether is subject to antenna currents. Specifically, lightning-storm activity is similar to a large untuned radio transmitter that transmits a multiplicity of spurious-frequency energy. Because any conducting-tether length always represents some multiple or fraction of a portion of the transmitted wavelength spectrum, tethers suffer from a high absorption cross section with respect to a large number of atmospheric electrical emissions. The displacement and antenna currents are considered particularly troublesome with respect to sensitive electronic equipment either on the ground (e.g., power supplies) or in the balloon, proper.

A close examination of Pierce's findings[11] suggests that if the product of the elevation of the balloon (involving conducting tether) and the electric field in the vicinity of the balloon (see Figure 5) exceeds approximately 10^6 V, then there is a high probability of initiating and being subjected to typical lightning currents. In Pierce's conceptual framework for lightning initiation, the dynamic effects of inserting a conductive element into high electrical fields are not emphasized as they were in Brook's studies[41]. However, it has been suggested by Pierce[44] that even a nonconducting tether will be subject to triggering lightning via the voltage discontinuity mechanism as a result of finite tether electrical conductivity and/or the presence of conducting surface films or absorbed moisture from the surrounding air.

If a conducting tether system were adopted for use with balloons, the protection schemes discussed below should be given consideration.

Balloon Protection

Lightning Rods. A lightning arrestor system is currently used with heavy-lift short-transport balloons for logging purposes (Raven Industries, Inc.). This lightning protection scheme involves a 3-m (10 ft)-high aluminum lightning rod positioned vertically at the top and center of the balloon with braided conductors connecting the lightning rod to the base of the rod support and then to the main tether. The tether (steel cable) is grounded. This balloon system is operated at altitudes below 300 m (1,000 ft) and does not contain any sensitive electronic equipment. Since adopting this lightning protection scheme, Raven Industries has accumulated 50,000 hours of operation without a serious lightning incident. Prior to adopting this scheme, a Raven Industries Model 240K was struck by lightning, but sustained no severe damage.

It is noteworthy that the success of the balloon-supported lightning arrestor scheme is critically dependent on the adequacy of the tether ground. For example, Hodkinson[45] reports that during a balloon ascent to an altitude of 1,000 m (3,300 ft) at Cardington, England, a lightning flash jumped from the "grounded" steel tether to the earth. At the time of the incident, the weather was overcast with a moderate sleet shower in progress and no other thundery activity was reported. It was evident that an electric discharge traveled down the steel tether which the grounding system was not able to accommodate. This problem is critical when dealing with conducting tethers as a small but critical resistance to earth is inevitable. Also, the "grounded" conducting tether is naturally exposed to rapidly changing potential gradients during disturbed weather conditions, particularly during periods of sleet or snow showers.

Catenary Wires. A similar lightning arrestor scheme was developed by Davis and Standring in England in the early 1940's for balloons with conducting tethers. This protection system included a 2-m (6.6 ft)-long lightning rod attached to a 1-m (3.3 ft)-high support. The support was mounted above the nose of the balloon together with a copper tape running to the top edge of each of the upper two fins (see Figure 7). These tapes, which form a bridge between the nose and the tail fins, provide protection similar to that afforded by the grounded wires positioned parallel to and above power transmission lines. This system of catenary wires is designed to provide an envelope of protection which includes the entire balloon. However, the catenary wires have the same vulnerabilities as those of the conducting tether, viz., susceptibility to displacement and antenna current surges. These current surges, through electromagnetic coupling, induce lesser current surges in any conducting devices in the vicinity of the catenary wires.

Conductive Skin. In addition to providing lightning arrestors via lightning rods and catenary wires, those regions of the balloon which are probable lightning attachment points should include sufficient metal (conductor) cross-sectional areas to provide an adequately low resistance path for lightning discharge. Even if a nonconducting tether is used, the placement of metal foils or fabric (screen) can greatly reduce the damage which normally

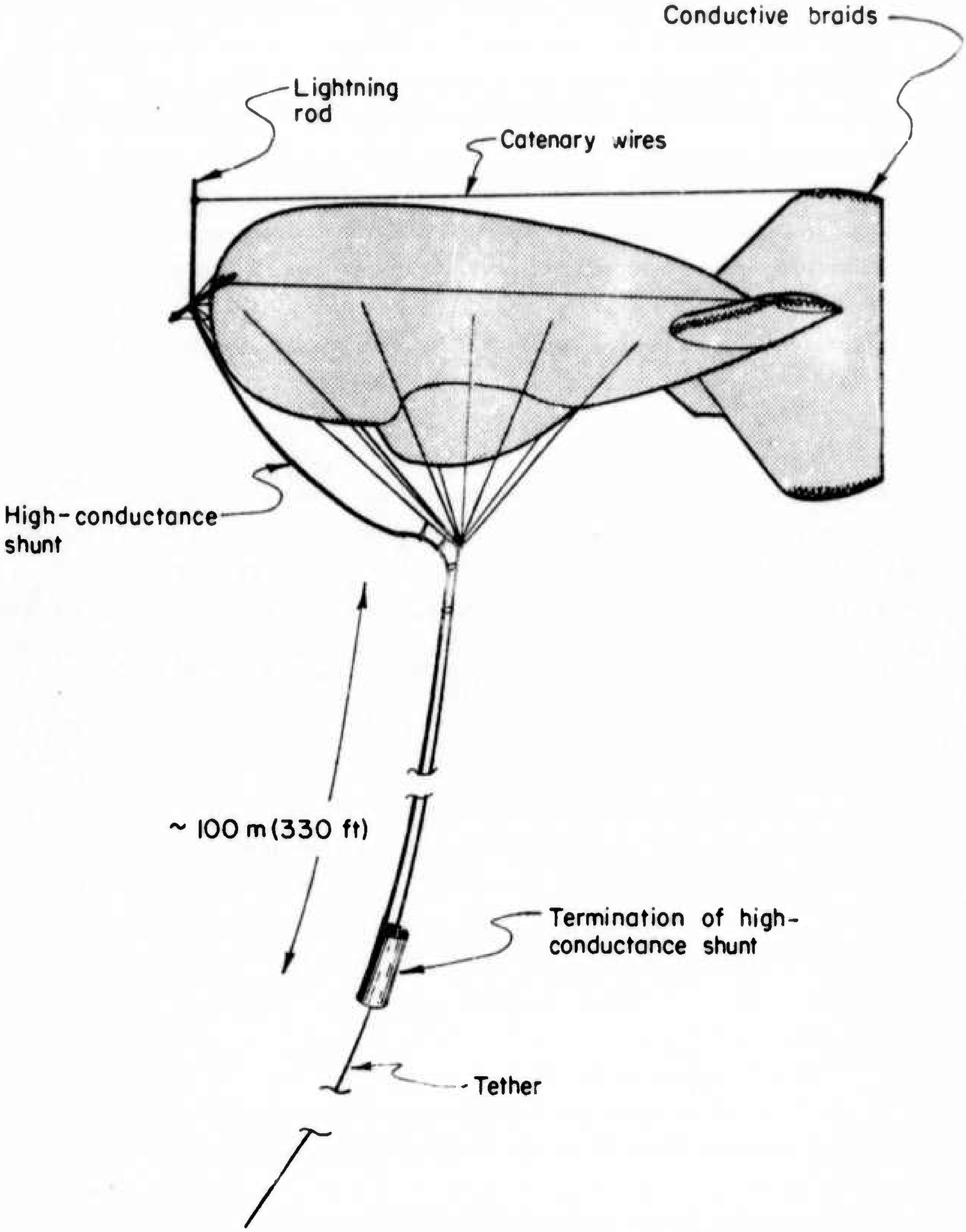

FIGURE 7. LIGHTNING PROTECTION SCHEME INVOLVING LIGHTNING RODS AND CATENARY WIRES

results from lightning attachment at a region of low electrical conductivity. For example, Quinliran(47) has demonstrated that conductive coatings of 120 x 120 and 200 x 200 mesh-per-inch aluminum wire fabric applied to nonconductive substrates withstood currents of up to 200 kA with little damage.

The foil strips and/or wire fabric should be positioned in those areas susceptible to lightning attachment as well as those "frontal" areas exposed to precipitation mechanisms. As in the case of aircraft with nonconducting radomes, the precipitation charging may result in charge concentrations sufficient to cause discharge and possibly triggering of lightning. Even if the discharge does not trigger lightning, it may lead to puncture of the nonconductive substrate (balloon fabric) and/or troublesome broad-spectrum radio interference as a result of spark discharges.

An estimate of the added weight of the 200 x 200-mesh aluminum wire fabric can be made using its known weight per unit area, viz., 0.244 kg/m^2 (0.05 lb/ft^2). For example, the coverage of the frontal areas only (including leading edges of the cruciform tails) for the ARPA Family II Balloons will add 40 kg (88 lb) to the total weight of the balloons. Laboratory-scale-model lightning studies may be an effective approach to identifying the critical attachment points under various environmental conditions.

Early Warning System

Several schemes have been suggested by Brook(41) and Stahmann(46) for early detection of disturbed (thundery) weather conditions. Stahmann's scheme involves the continuous monitoring of the atmospheric electrical field by measuring current flow in a fixed corona point. For detection of electrical fields (and more importantly their changes) below 1 kV/m, a radioactive corona point (polonium or radium) should be used. Alternatively, an electric field mill* should be used for accurate, sensitive, and reliable electric field measurements.

Brook suggests measuring current flow and rates of current change in the tether. These currents are on the order of milliamperes as compared with microampere current flows in corona discharge measurement schemes. Brook describes the range of currents and rates of change indicative of the initial stages of atmospheric electrical disturbances.

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* Available from Dayton Aircraft Products, Fort Lauderdale, Florida.

A third advanced warning system for thundery activity has been described by Cianos[29] and involves the positioning of two sensors at the extremities of the vehicle. This scheme is known as the Cianos-Oetzel-Pierce detector system and is currently being used on aircraft for the early detection of thundery activity. It is noteworthy that this scheme and that suggested by Stahmann are equally applicable to balloon systems with nonconducting tethers.

Personnel Protection

Stahmann[46] has suggested a number of schemes for protecting personnel on the ground. These schemes include a shield-cage cable follower to provide the protection of a Faraday cage for personnel required to handle the tether during power-line coupling, etc. Another approach to shielding personnel is the use of a lightning suit[46] comprising a conductive outer covering and an insulating inner liner to prevent parallel current paths in the body of the wearer. This approach affords greater mobility than that for the shield-cage cable follower but, conversely, offers a lesser degree of protection.

In addition to protecting personnel directly handling the power cable and/or conducting tether, a Faraday cage scheme is suitable for protecting any personnel in the vicinity of the ground operations (e.g., winch operator). The Faraday cage scheme is conventionally used to eliminate static electric fields inside the cage. However, Stahmann explains how the schemes can be extended to provide magnetic and electric shielding under dynamic conditions. These types of shielded enclosures appear mandatory for balloon systems with conducting tethers since there are numerous reported incidents of lightning jumping from a "grounded" wire to earth, a hazard aggravated by tethers at increasing angles with respect to the vertical position.

A protection measure for both personnel and ground-based equipment involves a properly designed surface ground plane. The interfaces between ground equipment and the tether (and power cable if used) are also described by Stahmann. In spite of a properly designed earth grounding system, all personnel should be aware of the possiblity of moderate-to-high static electrical charges on the cable or tether, even in clear weather. Also, separation of the cable or tether should not be attempted until a bridging cable has been placed around the planned disconnect.

Electronic Equipment Protection

The current-surge protection measures conventionally applied to sensitive ground-based equipment (e.g., computers), power transmission lines, and aircraft antenna subsystems (or other susceptible wiring) can also be applied to balloon systems. On the ground, these surge protection devices (e.g., thyrite surge diverters) may be used to protect low-current, high-voltage power supplies in a fashion similar to that described earlier for power transmission lines (see pages 24 through 27).

In airborne electronic subsystems, the thyrite surge diverter system may be required as well as band-pass filters and selective isolation protection schemes involving Thyrectors or their equivalent. The latter may be required in ground-based equipment where grounding both ends of cable shields increases the system noise levels due to ground-loop effects. The Thyrector allows one end of the shield to be isolated from ground, except in the presence of a voltage surge.

Where logic-based avionic systems (digital transmitters/receivers) are involved, a measure of protection (from second-order interference effects) can be achieved by incorporating protection measures into software systems, e.g., software error checks.

Where practical, Faraday cage enclosures should be used to provide electromagnetic shielding for sensitive electronic equipment. Rerouting, shielding, and twisting of wiring may help reduce transient voltage effects to an acceptable level.

A summary of the candidate protection measures for balloons with conducting tethers appears in Table 4. Although the "rating" of the various effects for each candidate protection measure is somewhat arbitrary, it does serve to illustrate the interactive nature of the schemes. In the next part of the discussion of protection schemes, attention will be focused on the nonconducting class of tethered balloon systems. In those cases where the protection measure has been discussed previously in the conducting tether section, only a reference will be given.

Protective Measures for Balloons With Nonconducting Tethers

The term "nonconducting", when referring to tethers, indicates that the tethers normally exhibit relatively large resistance (on the order of tens of megohms per meter of length). However, even with this large resistance, a balloon with a 1,000-m (3,300 ft) nonconducting tether will typically experience a voltage difference of 1 x 10^5 V and, hence, will suppo... finite current flows of approximately 10^{-5} A. If the nonconducting tether were to exhibit an effective resistance greater than or equal to that of the surrounding air, then it would be expected that a tethered balloon system should behave similar to aircraft. Accordingly, the lightning protection measures enumerated in the preceding section for aircraft and rockets (pp 28 and 29) should be directly applicable. However, the presence of surface contaminants, atmospheric deposits, surface moisture and absorbed moisture collectively increase the conductivity of the tether so that the ideal nonconducting condition is not usually maintained during actual operations.

In general, the literature and independent analyses indicate that the balloon system with a nonconducting tether presents fewer serious hazards during fair-weather operations. The lightning protection measures discussed below should further reduce the hazards to balloon, tether, personnel, and airborne electronic equipment. However, whether these protection measures will permit all-weather balloon operations will require verification through laboratory simulations and field evaluations.

Modified Tether Designs

In general, the effect of a lightning strike on a balloon system with a nonconducting tether can be minimized by making sure that all of the lightning current is carried on the external surface of the tether. If the current is transferred into the tether, as it could be with an interwoven power line, it is quite likely that the tether would be destroyed by the exploding power line much in the manner that a tree loses its bark when struck by lightning. For this reason, an uncovered nylon rope may be dangerous to use as moisture within the interstices of the rope will expand with explosive force if the tether is struck by lightning. Several approaches to protecting the nonconducting tether are discussed below.

One approach to tether protection (as well as personnel and balloon systems) is to prevent or limit those mechanisms which lead to an increase in the electrical conductivity of the tether. Three mechanisms which have been identified as increasing tether conductivity include: absorption of moisture through the outer layer of tether which resides in the interstices within the inner strands and at the rope-covering interface; accumulation of deposits on the surface of the tether (e.g., salt spray) which provide a continuous or intermittent path of relatively low resistance; and the decomposition (also referred to as "streaking") of the outer layer of the tether following the passage of a leader or return stroke resulting in a greatly increased conductivity.

An analysis of these degradation mechanisms revealed several protective measures. First, the problem of absorbed moisture has been encountered previously in the lightning protection of underground and overhead power transmission lines as well as other forms of electrical cable. One successful solution to this problem has been the oil or grease impregnation of insulation-covered cables in order to minimize the absorption and retention moisture inside the insulating sheath.

Second, the accumulation of conductive films has complicated the maintenance of high resistance in insulator strings and other high-voltage insulator systems, particularly in coastal regions. One very effective solution to this problem has been the coating of the insulator with special silicone compounds*. After the insulator (or in the present case, the tether) is coated, moisture forms into droplets and is restricted from forming a continuous electrolytic film on the substrate. In addition, the unit remains easy to clean, and, dirt and contamination deposited on the coated substrate are engulfed by the compound, effectively preventing the formation of a conductive path. This coating process is standard practice for high-voltage insulators in coastal regions of the U.S. It appears that this coating measure, together with the impregnation measure described above, will greatly reduce the rate or extent of degradation of the dielectric characteristics of the nonconducting tether. Care must be exercised in order to insure that the materials used in coating and impregnating the tether are compatible with the covering and the load-bearing materials.

A third solution to insulator or tether degradation involves the use of a "Teflon" FEP fluorocarbon outer covering in place of the presently used polyethylene covering. The Teflon covering offers several advantages including resistance to tracking and anti-stick surface characteristics. Specifically, the anti-stick surface of Teflon discourages deposit buildup and

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* For silicone compounds, see General Electric Technical Data Books S-21 and S-21B on *Silicone Greases and Compounds*.

will not form a highly conductive carbonaceous tract [as does the present NOLARO (PE)* covering] in the event that lightning discharge does occur. Should a discharge occur on a Teflon-covered tether, the arc merely ablates or "cleans" the surface, without charring or burning. Furthermore, the anti-stick surface characteristics of Teflon prevent strong adherence of contaminants and any buildup can be readily removed by rain or with a water spray. The maintenance requirements for the Teflon-coated tether should be much lower than for the silicone coating.

Another approach to protecting the nonconducting tether involves the use of a conducting ground wire [approximately 25 to 35 kg (50 to 75 lb) total weight] attached to the tether and maintained at a height of approximately 150 m (500 ft) above the ground as shown in Figure 8. This scheme should provide an additional measure of protection to ground operations as well as protection of the lower portion of the tether. The basis for this scheme is the result of several observations. First, Cianos has reported that peak surges during the return stroke phase of lightning discharge are not usually experienced at distances of more than 150 m above the ground. Above this level, the peak current surge drops off significantly. Hence, the use of a conductive shunt as shown in Figure 8 will protect the lower regions of the tether from these high surges. The approach of protecting the tether in regions closest to the ground is also in good agreement with the observed tether damage which resulted from the lightning stroke to a tethered balloon cable on August 18, 1972[48]. It was reported that the most extensive damage, in terms of length of tether affected, occurred along the tether closest to the ground [within about 100 m (330 ft) vertical height].

Another benefit of the grounded lightning arrestor wire is that it may serve to reduce greatly the incidence of lightning arcing between the tether (at some elevated point) and the ground below. As a result, the threat to ground-based personnel and equipment in the vicinity of the winch would be greatly reduced.

Balloon Protection

These protection measures are similar to those cited earlier for conducting tether systems except that the metal foils or fabric positioned at strategic locations on the balloon should be connected to precipitation static dischargers as well as to the nonconducting tether. For example, Golden[49]

*NOLARO (PE) tethers, manufactured by the Columbian Rope Company, are constructed of Dacron strands using a nontwist or no-lay construction technique and covered with a heat-set polyethylene jacket.

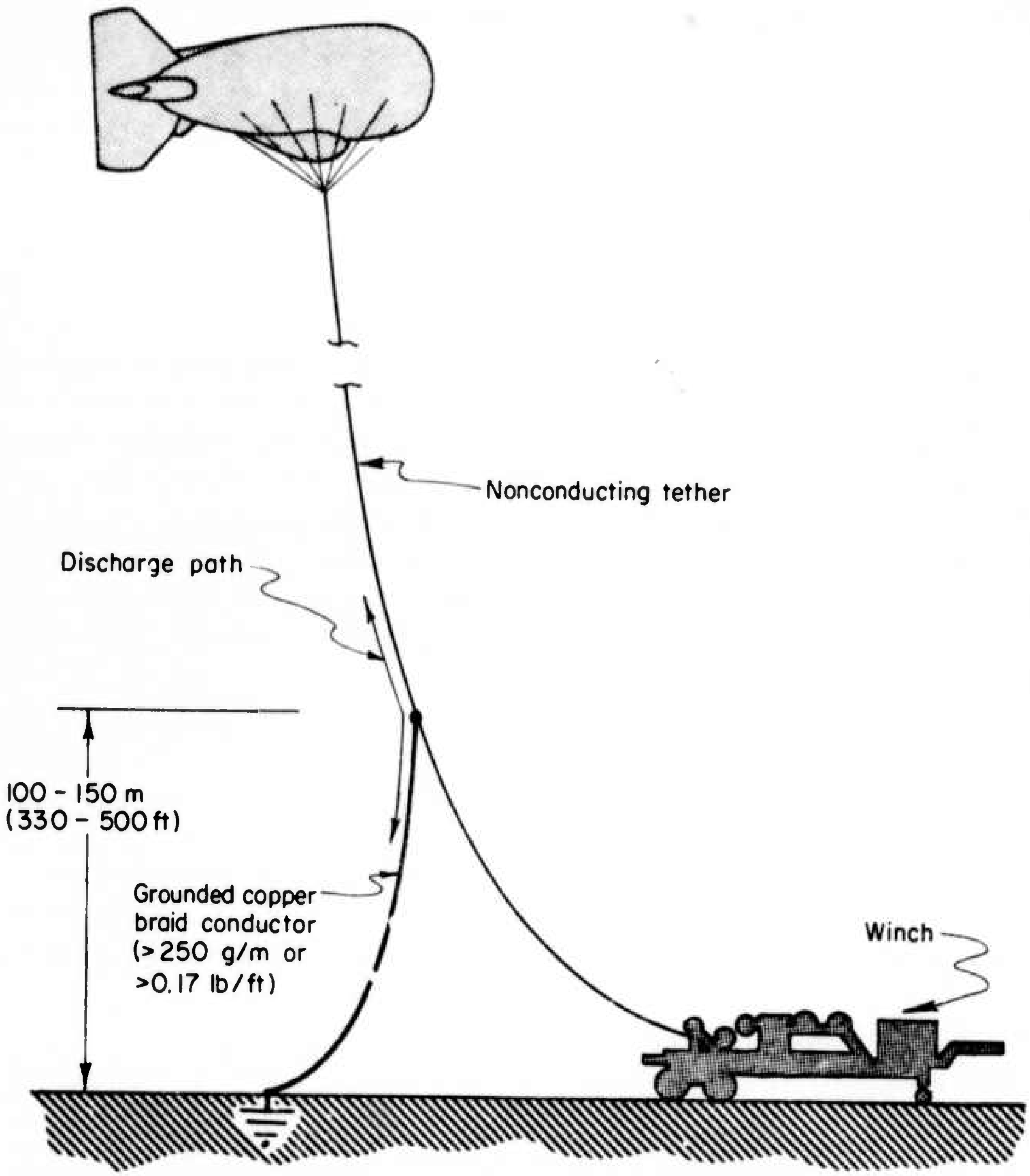

FIGURE 8. SUGGESTED SCHEME FOR REDUCING LIGHTNING HAZARDS TO GROUND-BASED PERSONNEL AND EQUIPMENT AS WELL AS LOWER REGION OF TETHER

suggests a scheme of transitioning girth wires leading from metal foils and fabric to the nonconducting tether with the objective of providing a path so that the lightning current can travel down the surface of the tether.

A totally different approach to balloon (and tether) protection involves providing a preferred path for the leader and return stroke discharge which is at a safe distance from the balloon. One approach to developing a preferred discharge path involves the use of a laser and is described in greater detail in the next section.

Early Warning System

See pages 48 and 49 for protection measures for conducting tethers.

Personnel Protection

See page 49 for protection measures for conducting tethers.

Electronic Equipment Protection

See page 50 for protection of conducting tethers. In addition, the use of active as well as passive systems[30] of static-electricity dissipation should be considered in order to prevent static-charge accumulation on or near sensitive equipment with accompanying broad-band radio interference.

Protection During Fueling Operations

The hazards of developing electrostatic charge accumulations during transfer of hydrocarbon fuels can be minimized by several methods including the use of relaxation tanks, fuel additives, and inerting of the vapor space above the fuel with nitrogen. A more detailed discussion of these protection measures was given under "Protective Measures for Aircraft and Rockets", pages 33 through 35.

Protection Via Flight Plan

The preponderance of strikes near the freezing level, as shown by Appleman[50], indicates a relationship to the negative charge center of most thunderclouds being found near this altitude. Appleman points to several suggestions for this relationship for aircraft; some of the suggestions are made here for tethered balloons:

- Balloons tethered in the general vicinity of the negative charge center may conceivably be struck by either intra-cloud or cloud-to-ground strokes.
- Balloons tethered to altitudes of 3,000 m (10,000 ft) above the negative center may intercept only intra-cloud discharges.
- Balloons tethered well below the freezing level may intercept only cloud-to-ground strokes.
- Conducting tethers extending through the freezing level [3,000 to 4,600 m (10,000 to 15,000 ft)] would most likely experience the most lightning activity at this freezing level.

Appleman has suggested a more plausible reason for the great preponderance of strokes near the freezing level. The negative charge is not located at a single point within a cloud, but is spread out with varying charge densities over a large volume. This also explains whey lightning strokes generally do not follow a simple straight-line vertical path from the negative region to the ground or between the negative and positive areas within clouds. Instead, the discharge travels nearly horizontally through much of the negatively charged region before turning up or down (Figure 9). This appears to be particularly true in the case of multiple-stroke discharges where one negative area discharges first, followed almost instantaneously by a discharge from a neighboring center to, and then along, the low-resistance ionized path formed by the first stroke, and so on[51,52]. Thus, a tethered balloon located near the freezing level would be far more likely to intercept a stroke than would a balloon operating well above or below the ± 5 C isotherms. However, the segment of the tether passing through this zone would be susceptible to lightning strikes.

A summary of the candidate protection measures for balloons with non-conducting tethers appears in Table 4. As was previously indicated, the "rating" of the various effects for each candidate protection measure is somewhat arbitrary. Nonetheless, it does serve to illustrate the interactive nature of the various protection schemes.

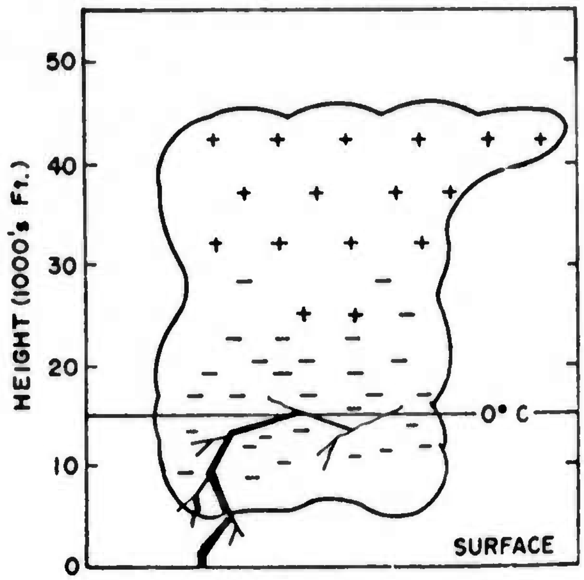

FIGURE 9. PATH OF LIGHTNING STROKE ALONG 0°C ISOTHERM Suggested by Appleman[50] and Schonland[52].

TECHNICAL FEASIBILITY OF AIR IONIZATION FOR STATIC DISCHARGE AND/OR LIGHTNING PROTECTION

Two advanced concepts utilizing radioactive lightning rods and laser-generated lightning discharge channels for the lightning protection of tethered balloons were evaluated. The results of these analyses are discussed below.

Radioactive Lightning Rods

The concept of radioactive enhancement of space-charge generation by lightning rods (and hence their protective range) has been evaluated by Müller-Hillebrand[53]. The suggestion to use radioactive materials for various aspects of lightning protection is by no means novel. However, claims have been made in recent years to the effect that a single rod of normal height, if fitted with a radioactive tip (i.e., having radioactive emanations which will ionize the surrounding air), is capable of protecting an entire building of large horizontal dimensions.

In order to test the effectiveness of a radioactive lightning conductor, Müller-Hillebrand erected four of these devices at distances of between 31 and 53 m (100 and 175 ft) along with a conventional lightning rod of the same height (approximately 10 m) as the radioactive lightning rod. He then recorded the point discharge currents produced by the two types of rods under thunderstorm conditions in Switzerland and Sweden. The results of these investigations are summarized in Figure 10. These curves show that, for small gradients of 0.5 kV/m or less (i.e., distant thunderstorms), the normal lightning rod produces no measurable point discharge current whereas the radioactive lightning conductor discharges currents of the order of a fraction of a microampere. However, as a thunderstorm moves closer and the electric field intensity increases, the curves begin to merge - hence, normal corona discharge under large electric field intensities masks out any radioactive enhancement effects. The radioactive lightning rods used in these experiments involved radium coating on the surface of the rod.

If it is assumed that the current discharged into the atmosphere by a lightning rod is indicative of its attraction action, then it must be concluded that a radioactive lightning rod provides the same degree of protection as a conventional conductor of the same height above the ground. The British Code[54] is in agreement with this conclusion and indicates that no artificial means are known by which to increase the range of attraction afforded by a lightning conductor.

The effectiveness of radioactive sources for producing sufficient space charge to suppress lightning attachment (due to lowered electric field intensities in the vicinity of high space charge concentrations) has also been considered. Two parameters are of interest in evaluating this mechanism for lightning protection: the range of the ionizing particles and the ion density (inferred from point discharge currents).

First, the ion density or point discharge currents attributable to the radioactive lightning rods have been shown[53] to be well below the naturally occurring corona discharge currents during thundery conditions (i.e., high ambient electric fields). Hence, it does not appear that radioactive sources will afford any significant increase in discharge rate during thundery conditions.

Second, the range (in air) of the emanations from the radioactive source is also an important aspect of this concept. Table 5 summarizes the maximum range in air of α- and β-particles for selected particle energies. For example, strontium (Sr^{90}) having a maximum β-particle energy of 0.545 MeV would provide a maximum range of ionization of approximately 1.5 m (5 ft). The relatively short range of the α-emitters makes them impractical for consideration in applications where range is important. To achieve greater ranges with β-particles requires particle energies well above 1 MeV, the threshold for

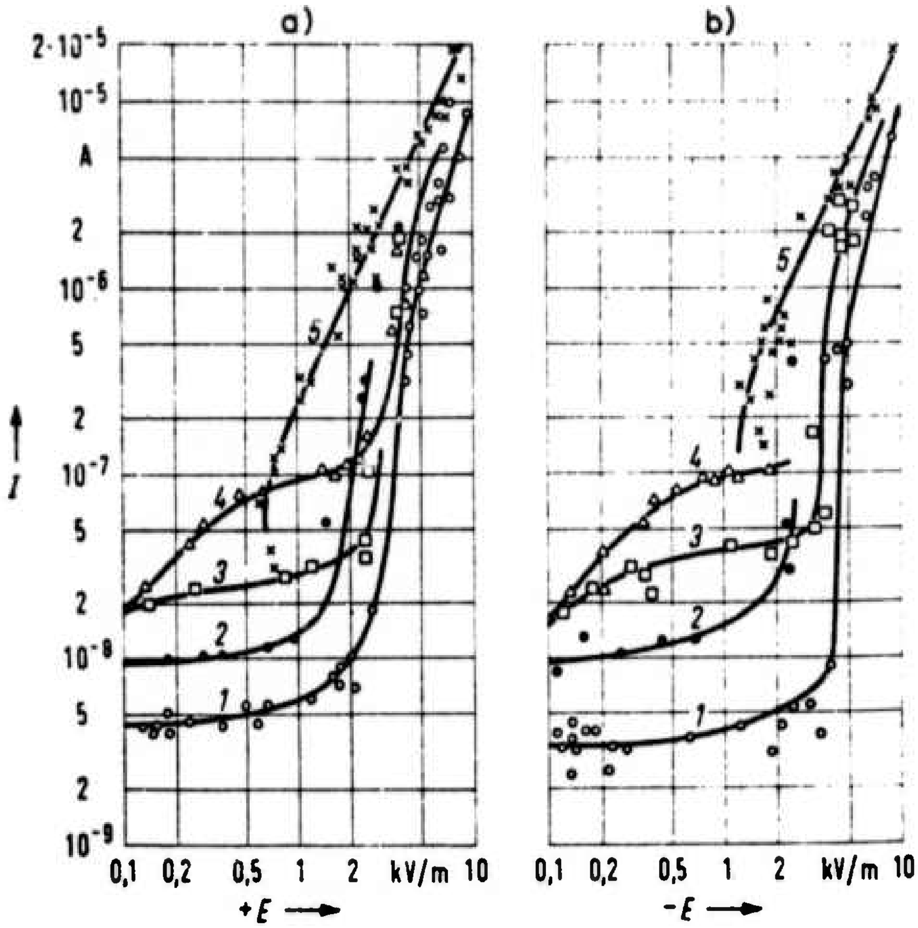

FIGURE 10. VARIATION OF EMISSION CURRENT WITH ELECTRIC GRADIENT

a) Positive gradient; b) negative gradient; 1, 2, 3, 4 = radioactive lightning conductor; 5 = normal lightning conductor. From Reference 53.

TABLE 5. RANGE AND AVERAGE ENERGY OF IONIZING PARTICLES

Energy of Particle, MeV	Maximum Range in Air, cm	
	α-Particle	β-Particle
0.1	0.10	9.33
0.6	0.38	148
1.0	0.52	292
2.0	1.01	659
5.0	3.52	1,690
8.0	7.36	2,710

biologically hazardous Bremsstrahlung emanations. This latter type of emanation would greatly limit the activities of personnel in the vicinity (within tens of meters) of the balloon. In addition, the radioactive emanations must be considered with respect to their potential radiation damaging effects on the balloon systems, particularly in the fabric.

Shaeffer[19] also investigated the effect of a radioactive polonium (Po^{210}) strip on breakdown voltage of air between disk-shaped electrodes. In this experiment, the radioactive strip was positioned between the electrodes (16 cm was the maximum distance from electrodes) and the effect in reducing the breakdown potential was recorded. In the case of Po^{210} (α-emitter with a maximum range of ∿4 cm in air), the effect was dependent on the direction of the emanations (no effect observed with source directed at right angles with respect to the electric field.)

Laser-Generated Lightning Discharge Channels

A detailed review of current knowledge concerning the effects associated with the passage of laser beams through gases suggests that a sufficiently intense laser beam may provide a path along which a spark can be directed. Oman[7] describes the "conventional" discharge path as one determined by a streamer which propagates by means of ionization avalanche processes occurring at the tip of the streamer. In the tip region, where the streamer diameter is small, the electric field is intense enough to maintain a Townsend coefficient* sufficiently large for electron multiplication. The resulting high electron density increases the conductivity of progressively advancing regions and so lengthens the streamer, while maintaining a small tip radius. The process normally continues until the tip potential falls below a threshhold value or until the stream completes the path (e.g., cloud to ground) across which a high current discharge can occur (i.e., return stroke). In contrast to this conventional process, Koopman, et al.,[56] have shown that, if a preliminary channel were defined in which the cascade ionization process were more rapid or efficient, a streamer would tend to follow this preferred channel. Hence, it may be feasible to use a laser to provide a preferential path for a lightning discharge. Several approaches by which a laser might be employed for this purpose are discussed below. Following this discussion, some of the implications of laser-guided lightning discharge with respect to tethered balloon protection, are considered.

High-Level Ionization

Previous studies have shown that the laser can be used in several ways to influence electrical breakdown phenomena in gases. First, high-level ionization has been produced by the passage of focused, Q-switched laser beams through air. In this case, visible or optical breakdown is clearly evident and is accompanied by substantial energy absorption and brilliant luminosity with very high levels of ionization produced in or or more small regions. For example, Hagen[57] has used a neodymium-glass laser system, emitting a 4 gigawatt diffraction-limited pulse at a radiance of 2×10^{17} w/cm^2 (ster), to produce a chain of air-breakdown points extending out to 38 m (125 ft)**. These air-breakdown points were generated using a 28-m-focal-length lens and they extended 10 to 15 m (33 to 50 ft) on either side of this focal point.

*The first definition of the Townsend coefficient, which is applicable here, is: the number of ion pairs formed by an electron in each centimeter of drift toward the central wire of a counter and is a function of the electric field strength, nature of the gas, and the gas pressure.

**In this experiment the length of the discharge chain was limited by the length of the room, and not by the lack of laser power.

The occurrence of a string of air-breakdown points (as opposed to a single breakdown at the focal point) is the result of a self-focusing effect within the laser beam due to induced changes in the index of refraction of the air within the beam. These changes in index of refraction produce a focusing effect which provides, at intervals, beam intensities sufficient to cause air breakdown.

If a string of air-breakdown points could be produced over very long path lengths (approaching thousands of meters), then it is conceivable that a preferred path for lightning discharge might be obtained. Koopman[56] has experimentally demonstrated that a laser beam is capable of defining a preferred channel in which an enhanced cascade ionization process occurs. Specifically, Koopman clearly demonstrated that channeling occurred over a distance of 25 cm (1 ft) at laser powers of 1.5 to 2.5 gigawatts in electric fields of approximately 550 kV/m (spontaneous spark discharge in air normally occurs above 730 kV/m). Koopman concluded that, at higher laser output, channeling should be attainable over longer distances or lower electric fields (i.e., below 550 kV/m). During a recent conversation with Koopman[58], it was learned that laser-channeled electrical discharges have been extended to distances of up to 1 m (3.3 ft).

It appears that there are several important considerations in assessing the feasibility of applying lasers to the protection of tethered balloons from lightning. First, present observations of laser guiding mechanisms[56] do not indicate whether laser-induced optical air sparks are essential for guiding. If, in fact, laser power levels below air-spark levels are sufficient, lightning channeling should be possible with subtantially lower energy consumption per meter traversed. This leads to the possibility of guiding lightning strikes over long distances with state-of-the-art laser systems. This suggests a second, and possibly more critical, consideration. Specifically, it appears that the previous laboratory experiments may be dealing primarily with the effect of laser-beam channeling of direct electrical discharges. Hence, the previous laboratory investigations may not be representative of the effect of a laser beam on the naturally occurring stepped-leader stage of the lightning discharge process. The influence of a laser beam on the path of a stepped leader might be meaningful assessed only in naturally occurring lightning environments[59]. Thus, it may be possible to effectively channel a naturally occurring stepped leader over long distances with practical laser systems - in contrast to triggering and channeling a lightning discharge by providing an artificially produced "leader".

A preliminary analysis was undertaken to identify what parameters might be important in the laser channeling of naturally occurring stepped leaders. This analysis is summarized in Appendix B and suggests that it may not be necessary to achieve a large value of electron density, N_e, in order to channel a stepped leader. Rather, it may be sufficient to achieve some threshhold space gradient of the electron density, ∇N_e. This suggests that the aforementioned requirement might be achieved by the production of free electrons below optical breakdown levels. More detailed analysis is necessary, however, in order to assess the feasibility of an artificially guided stepped leader involving laser beams operating below optical-breakdown intensities.

Low-Level Ionization

Several investigators[60,61] have demonstrated the ability of lasers to trigger electrical sparks over short distances, even though the laser beams produced no visible optical breakdown. Pendleton[59] concludes that the initiation or triggering of a spark discharge with low-intensity laser beams (i.e., at beam intensities below optical breakdown in air) is probably due to localized field distortion. Specifically, localized oscillatory electrical fields in excess of 10^9 V/m are expected at the focal point of the lens. Kleme, et al.,[60] conclude that laser-induced gas ionization occurred in their spark-triggering experiments, even though no visible laser "spark" could be observed. Furthermore, it is concluded that the breakdown properties of an electrode gap are likely to be altered if appreciable ionization has been formed in the gap prior to applying the potential across the gap.

These results suggest that, even below threshholds of optical breakdown in air, laser beams can influence electrical discharge processes.

Applicability to Tethered Balloon Protection

The foregoing discussion indicates that it may be possible to guide lightning discharges from cloud to ground, preferably without triggering the lightning. The most promising form of laser protection would be that of providing a preferred path for naturally occurring stepped leaders without the attendant formation of air breakdown (or spark strings) along the entire length of the path between the cloud and the ground. The presence of these spark discharges is undesirable from the standpoint of both laser power consumption and the wide-band radio interference which would result.

To be most effective, the laser channeling system should not serve to trigger lightning discharges. Otherwise, the tethered balloon system would be subjected to frequent triggered lightning discharges in its immediate vicinity; the ground personnel, electronics, and tether would be unnecessarily exposed to hazards of displacement currents, antenna currents, and related phenomena. Hence, to be useful, the laser protection system should provide a preferred path in the vicinity of the tethered balloon, in the event that a nearby, naturally occurring lightning discharge takes place.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Clearly, there is a growing interest in atmospheric electrical protection throughout government and industry. In the past several years particular emphasis has been placed on the protection of aircraft, rockets, cargo helicopters and their personnel from lightning and static electricity hazards. Therefore, the lightning protection system developed for these and other related engineering systems should continue to provide an important technology base for the development of atmospheric electrical protection schemes for tethered balloon systems. Based on the present study, several general conclusions can be drawn regarding the protection of tethered balloons.

It appears that the concept of a "nonconducting" tether, to the extent that it prevents the balloon from experiencing ground potentials, is not practically attainable under all weather conditions. For example, the electrical resistance of a nonconducting tether (e.g., 15,000 MΩ/m) may be greatly reduced due to the presence of contamination on the surface of the tether (e.g., salt water deposits) as well as moisture absorption. Although several approaches can be taken to minimize the electrical degradation of nonconducting tethers, it appears that electrical currents will continue to flow in the tether and, in time, will "charge" the balloon to near ground potential. Precipitation charging may tend to offset or add to this charging mechanism depending on the polarities involved. Maintaining high electrical resistances within the tether will serve to slow down the charging of the balloon. Consider, for example, the charging times for a typical 5,500 m^3 (200,000 ft^3) balloon involving selected tether resistances as shown in Table 6. These estimates show that for large tether resistances, the charging rate is sufficiently large to allow the balloon to be charged to one-tenth of the ground potential within a period of 8 hours.

Second, there are a number of measures that can be taken to minimize the frequency of triggering lightning. These measures will not directly affect the ability of the tethered balloon system to withstand a lightning strike but, rather, to minimize the frequency of these occurrences. These measures include: the elimination of structural shapes which may lead to the intensification of electric fields; the means for distributing and dissipating precipitation-static charges; and the minimization of the potential difference between the balloon and the surrounding atmospheric charge fields. With regard to the latter measure, any attempt to match the potential on the balloon with a given atmospheric charge center will render the balloon vulnerable to cloud-to-cloud lightning discharges.

Third, several protection schemes have been identified which should provide an additional measure of safety for the ground personnel. These protection schemes include Faraday cages for personnel in the immediate area of the tether; a high-electrical-conductivity shunt cable (grounded) attached to the tether and maintained at a height of 100 to 150 m (see Figure 7); and the adoption of fueling precautions to avoid static charge accumulation and possible ignition of the fuel.

The protection of the balloon and its payload from lightning damage can be enhanced by providing a system of conductive paths, e.g., catenary wires, along the extreme regions of the balloon and connected to a shunt wire which terminate approximately 100 m (350 ft) below the tether confluence point (see Figure 7). Additional protection of the payload can be provided by the use of secondary shielding, e.g., Faraday cages, in conjunction with surge-protection devices similar to those developed for aircraft.

In general, the protection of the tether can be enhanced by minimizing the chances of moisture absorption into the interstices of the cable since direct or nearby strikes will often cause induced currents sufficients to create an explsoive reaction within the cable due to vaporization of the fluid. Likewise, the results of this study indicate that if electrical power

TABLE 6. COMPARISON OF BALLOON POTENTIAL RELATIVE TO GROUND FOR SELECTED TETHER RESISTANCES

Elapsed Time, hr	Potential of Balloon as a Percent of Ground Potential[a]			
	R = 15,000 MΩ/m[b]	1500 MΩ/m	100 MΩ/m	1 Ω/m
1 min	0.03	0.3	3.3	∿100
10 min	0.3	2.2	28	∿100
2	2.7	24	98.2	∿100
8	10.1	66	∿100	∿100
24	27.4	96	∿100	∿100

(a) $V_{balloon} = V_{ground} (1 - e^{-t/RLC})$,

where

t = elaped time, sec

R = tether resistance, Ω/m

L = 1,500 m - length of tether

$C = 1.2 \times 10^{-8}$ farad - capacitance of balloon.

(b) Corresponds to a material resistivity 7.5×10^{8} ohm-cm.

is to be transmitted from the ground to the balloon via electrical conductors, the conductors should be located at exterior regions of the tether and not imbedded inside the tether since direct or nearby strikes may induce sufficient current flow to cause excessive damage inside the tether. For example, if the induced interior heating is confined, the effects may severely weaken the surrounding nonconducting load-bearing tether. The desirable electrical resistance features of a nonconducting tether can be protected from environmental effects (accumulation of surface deposits, streaking due to surface stroke) in several ways. One measure involves the application of protective coatings on the tether such as specially developed silicone coatings. An alternative measure involves the use of tether surface coverings, e.g., Teflon materials, which resist electrical "streaking" and the accumulation of electrically conductive surface deposits.

Based on the results of this study, it also appears that a totally different approach to lightning protection may be possible, viz., the artificial creation of a preferred path for the lightning leader using lasers. Specifically, the preliminary analysis undertaken in this study suggests that it may be possible to create sufficient space-charge gradients with lasers to guide the path of a cloud-to-ground leader. It appears that this may be more practically attainable (and more desirable, as well) than to create a highly ionized path from the ground to the balloon which will directly accommodate (and likely, trigger) atmospheric electrical discharges.

A second concept for balloon protection involving radioisotope-enhanced lightning rods was examined. The study revealed that under thundery conditions the naturally occurring rates of electrical discharge from lightning rods greatly exceeded those rates attained by lightnings rods coated with practical quantities of radioisotopes.

In summary, it can be concluded that a number of measures can be taken to provide additional protection for tethered balloon systems. Most of these measures can be applied to the present nonconducting tethered balloon systems with only minor changes in either the total balloon weight or its configuration. It cannot yet be ascertained whether or not these lightning protection measures will permit continuous operation (or at least, survival) of the balloon system under all weather conditions. The answer to this question depends, in part, on the practicality of providing an artificially produced, preferential path for cloud-to-ground leaders. Even the "success" of this advanced concept may not protect the balloon system from cloud-to-cloud discharges. Also, the results of this study suggest that the trade-off between conducting and nonconducting tethers should be reevaluated since there is no clear evidence that a nonconducting tether is significantly safer (with respect to lightning effects) than a conducting tether (e.g., a nonconductive core with conductive wires for power transmission).

A number of specific recommendations can be drawn from this study. These involve both the enhancement of lightning protection for the present nonconducting tethered balloon systems as well as the evaluation of advanced protection schemes for future balloon systems. An enumeration of these recommendations appears below.

Recommendations

Before proceeding with the enumeration of specific recommendations it should be recognized that the designation of the overall lightning protection scheme for a given engineering system is complicated by a number of factors.

First it has been shown that certain lightning protection measures are often dysfunctional with respect to other aspects of the system. Consequently, the specification of a lightning protection scheme presupposes priorities as to the order of protection provided to the various aspects of the system. Accordingly, no single protection measure is sufficient for a system as complex as the tethered balloon system. Rather, a combination of measures is recommended in order to provide the degree of protection needed for each aspect of the system.

Second, the statistics which characterize lightning have been almost entirely deduced from ground observations. Consequently, the resulting models for lightning discharges to earth represent essentially the current-time and charge-transfer histories at each point where the discharge contacts the ground. Although these models can be confidently applied in the case of ground-based equipment, they provide a conservative (more severe) estimate of the lightning exposure for aircraft, rockets, or tethered balloons. As mentioned earlier in the discussion on tether protection, the 100 to 150 m (330 to 500 ft) of tether located just above the ground will usually be exposed to the most severe lightning damage.

A third factor complicating the specification of lightning protection schemes is the variety in the type and degree of the atmospheric electrical disturbances. For example, the optimum protection scheme for tethered balloons should be tailored to such factors as the geographical location, mission profile (time period, altitude of operation), and season.

Specific recommendations are outlined briefly below:

A. Balloon Systems With Nonconducting Tethers

(1) Evaluate the feasibility of minimizing absorption and transport of moisture into interstices of the tether by oil or grease impregnation of the tether interior (region within outer polyethylene covering). The evaluation should include exposure of selected tether samples to simulated lightning environments.

(2) Evaluate the feasibility of coating the exterior of conventional nonconducting tethers with specially developed silicone compounds to prevent electrical streaking and minimize the effects of surface contaminants on the electrical resistance of the tether. The evaluation should include exposure of selected tether samples to simulated lightning environments. This measure is recommended as an adjunct to the oil impregnation of the cable (see Item A-1 above).

(3) As an alternative to the use of silicone coatings, evaluate the feasibility of using tether coverings such as Teflon FEP fluorocarbon in place of the present polyethylene covering. Although a Teflon FEP fluorocarbon covering may more than double the cost of the present NOLARO (PE) tether, it features a high resistance to electrical streaking and resists the adherence of surface deposits and likewise is readily cleaned by simple rinsing operations. As before, the evaluation of this measure should include exposure of selected tether samples to simulated lightning environments.

(4) Evaluate the feasibility of using active or passive static dischargers on the balloon extremities and connected to a network of conducting ribbon or fabric to minimize the

accumulation of large precipitation-static charge levels. This problem is most critical at the frontal areas of the balloon and in regions with small radii of curvature (e.g., leading edges). If a conductive paint is used on balloon fabric, then static dischargers may be strategically located at extreme points of the balloon (in order to inject static charge into the slipstream) without the need for conductive ribbon or fabric.

(5) Undertake a detailed examination of the hazards associated with transferring hydrocarbon fuels from the ground to the balloon generator system since the static charge associated with fueling aircraft suggest some potential dangers. Protection measures to be considered should include the use of relaxation tanks, fuel additives, inerting of the vapor space above the fuel, and selection of the fuel.

B. Balloon Systems With Conducting Tethers

(1) Evaluate the feasibility of tether designs involving nonconductive inner core and conductive power transmission leads near the exterior of the tether (see Figure 11). The advantages of this approach include adaptability to conventional nonconducting tethers [e.g., NOLARO (PE) cable] and location of lightning-sensitive conductive elements on the exterior of the tether in order to minimize any damage to the load-bearing, nonconductive core. Also, this evaluation should include exposure of selected tether designs to simulated lightning conditions.

(2) Evaluate the feasibility of using current-surge protection devices to minimize damage or disruptive effects with respect to ground-based equipment, power transmission leads, or airborne electronics. For example, thyrite surge diverters may be suitable for protecting ground-based, low-current, high-voltage power supplies.

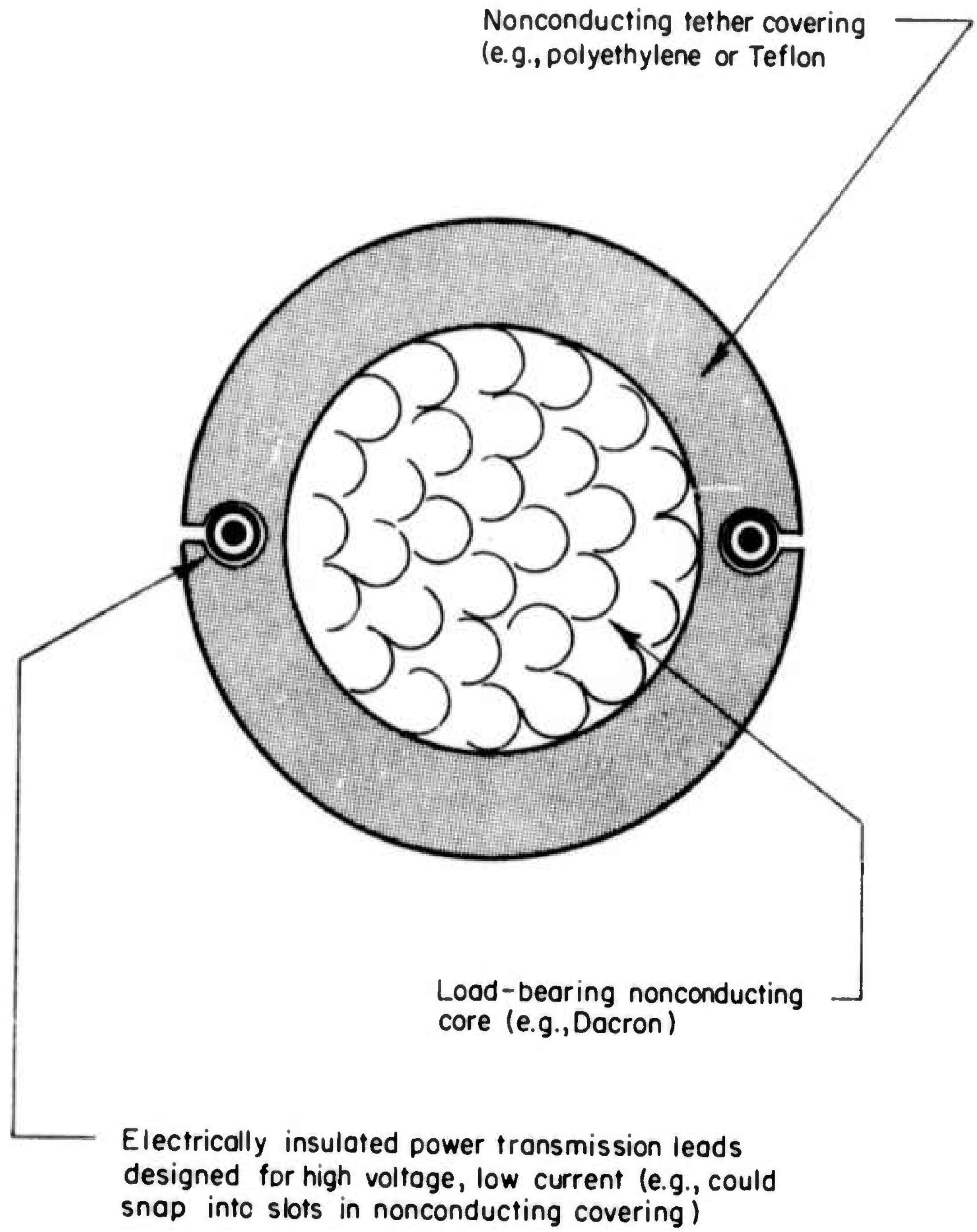

FIGURE 11. SUGGESTED TETHER DESIGN FEATURING CONDUCTING POWER TRANSMISSION LEADS AND NONCONDUCTING, LOAD-BEARING CORE

C. Balloon Systems With Either Conducting or Nonconducting Tethers

(1) Evaluate the feasibility of using high-conductance shunt cables in the vicinity of ground-based personnel and equipment as shown in Figure 8 (page 54). This shunt should serve to divert the path of a lightning discharge away from ground-based personnel and equipment. Also, the shunt will protect the lower regions of the tether which are otherwise exposed to the peak surges normally occurring 150 m (500 ft) above the earth. This scheme may be suitable for either nonconducting or conducting tether systems. It may be possible to evaluate the effectiveness of this scheme using scale models exposed to simulated lightning conditions.

(2) Evaluate the feasibility of attaching a network of catenary lightning protection wires to the exterior regions of the balloon as shown in Figure 7 (page 47). This scheme should include a high-conductance shunt wire in order to channel the lightning stroke away from the balloon and onto the lower regions of the tether. Under conditions of large vertical electric fields, this shunt will also serve to enhance the susceptibility of lightning attachment to the catenary wires as opposed to the balloon proper. This protection scheme is somewhat similar to that used for ground-based power transmission lines. Also the catenary wires will normally provide a zone of protection such that lightning (even without large vertical electric fields) will not strike the balloon proper.

(3) Evaluate an alternative or supplementary protection measure involving circumferential conductive braids to allow the balloon to accommodate cloud-to-cloud discharges without severe damage. This would not necessarily require a complete conductive covering over the balloon but rather strips of conducting foil or fabric at selected intervals. As in Item C-1 above, this scheme may be evaluated using scale models exposed to simulated lightning conditions. Also, any any regions of the balloon highly susceptible to lightning

attachment should be covered with aluminum fabric (fine mesh screen) to dissipate discharges without damaging balloon fabric.

(4) Evaluate the effectiveness of ground-based and/or airborne early warning systems. One form of warning is that of ambient temperature since previous aircraft flight records indicate that approximately 80 percent of all strikes occurred when the aircraft was flying in air at temperatures ranging from -5 to +5 C. Also, sophisticated detection equipment is being developed for aircraft to provide advanced warning of thundery weather conditions. If this early warning system were used in conjunction with an electrical power storage system, then all ground-based power transmission could be automatically terminated during periods of threatening weather conditions by simply switching the airborne electronics over to batteries located on the balloon.

(5) Undertake a comprehensive evaluation of the feasibility of using lasers to artificially produce a preferred path for cloud-to-ground leaders. This concept may not only provide a significant advancement in lightning protection technology for balloons, but may also be a key to protecting a wide range of systems--not only from the direct effects of lightning discharges, but the indirect effects such as damaging winds (e.g., tornadoes) which accompany these atmospheric electrical phenomena.

(6) Undertake detailed studies of tethered balloon flight plans which may serve to minimize the hazards of lightning strokes for a given geographical location, season, and time of day.

(7) Examine the suitability of an independent sheave concept whereby the tether can be brought into close proximity of the ground but at a safe distance from the winch operator and other ground-based personnel and equipment. This concept is shown in Figure 12. This measure is an alternative to Item C-1 above and, likewise, may be

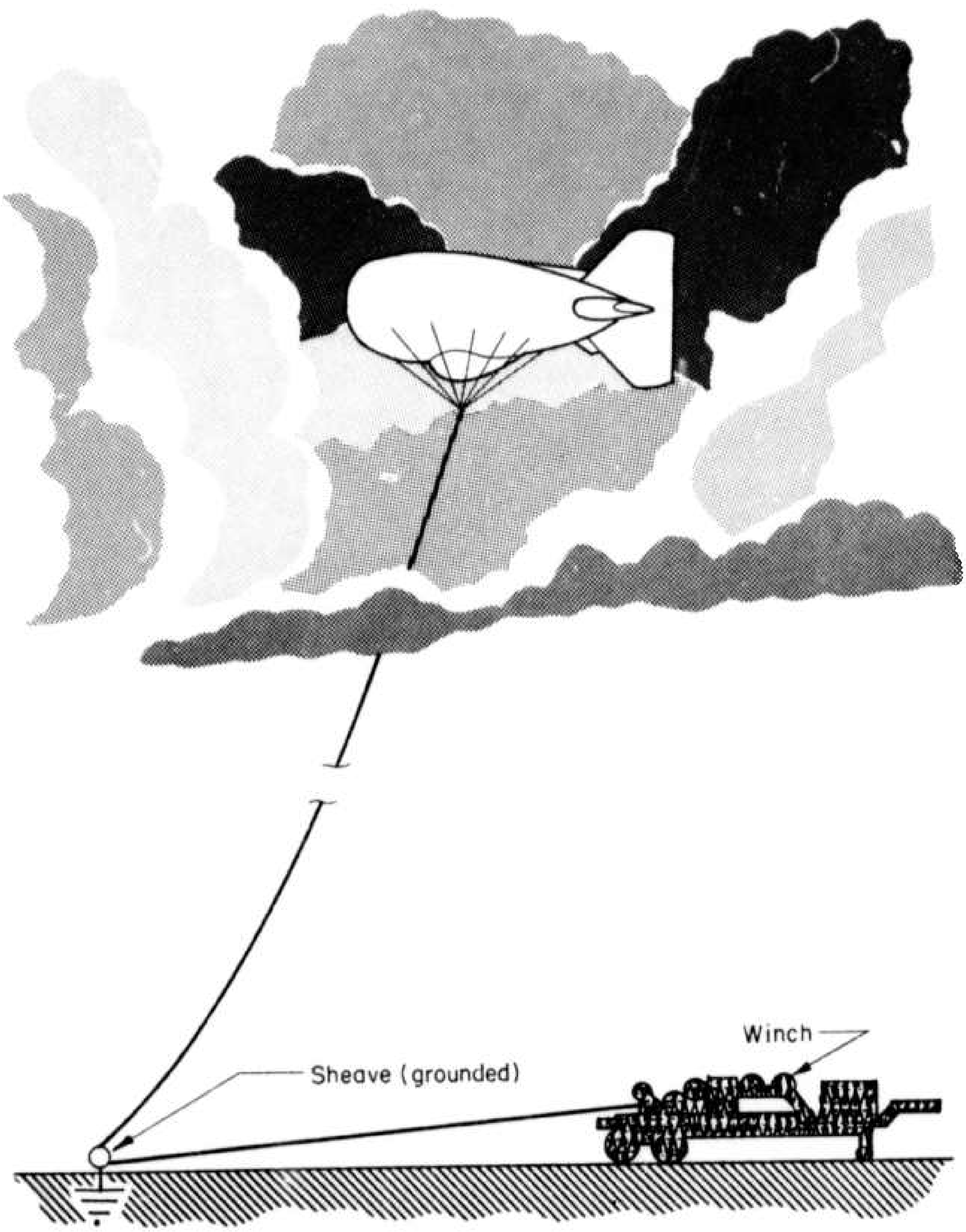

FIGURE 12. CONCEPT FOR PROTECTION OF GROUND-BASED PERSONNEL AND EQUIPMENT INVOLVING REMOTE SHEAVE

evaluated using scale models exposed to simulated lightning conditions.

(8) Examine the feasibility of instrumenting tethered balloons so that the relative rates and polarities of balloon charging via leakage through tether and precipitation charging can be assessed.

(9) Examine the adequacy (in terms of impedance and region affected) of present grounding systems in the vicinity of ground-based personnel and equipment. (See earlier discussion of grounding considerations for buildings and towers).

REFERENCES

(1) Pierce, E. T., "Some Topics in Atmospheric Electricity", a selection in Recent Advances in Atmospheric Electricity, Smith, L. G. (Editor), Proceedings of the Second Conference on Atmospheric Electricity, Portsmouth, New Hampshire, May 20-23, 1958, Symposium Publications Division, Pergamon Press, New York (1958)

(2) Adams, N. A., "Introduction to Lightning and other Electrostatic Phenomena", Technical Report 224, Air Weather Service (MAC), United States Air Force (August 1971).

(3) Malan, D. J., Physics of Lightning, The English Universities Press Ltd., London (1963)

(4) Pierce, E. T., "Latitudinal Variation of Lightning Parameters", J. App. Meteorology, Vol. 9, pp 194-195 (1970)

(5) Cianos, N. and Pierce, E. T., "A Ground Lightning Environment for Engineering Usage", Technical Report No. 1,Stanford Research Institute, Menlo Park, California, Contract No. LS-2817-A3, SRI Project No. 1834 (August 1972).

(6) Cianos, N., and Pierce, E. T., op. cit., p 95.

(7) Oman, M. A., Lightning, McGraw-Hill, New York (1969).

(8) Cianos, N., and Pierce, E. T., op. cit., pp 60, 100.

(9) Cianos, N., and Pierce, E. T., op. cit., p 111.

(10) Cianos, N., and Pierce, E. T., op. cit. p 73.

(11) Pierce, E. T., "Triggered Lightning and Its Applications to Rockets and Aircraft", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972).

(12) Cohen, I. G., "Benjamin Franklin's Experiments, letter to M. d'Allibard, June 29, 1755, Howard University Press, Cambridge, Massachusetts (1941).

(13) Golde, R. H., "The Lightning Conductor", Journal of the Franklin Institute, Vol. 283, No. 6, p 451 (June 1967).

(14) National Fire Protection Association, "Lightning Protection Code", NFPA Standard No. 78-1968, p. 14.

(15) Fisher, F. A., "Protection of Ground Space Facilities From the Effects of Lightning", 1970 Lightning and Static Electricity Conference (December 1970), p 310.

(16) Wagner, C. F., "Lightning and Transmission Lines", Journal of the Franklin Institute, Vol 283, No. 6, p 558 (June 1967).

(17) Young, F. S., et al., "Shielding of Transmission Lines", IEEE Transactions, Power Apparatus and Systems, Special Supplement, Vol 582, pp 132-154 (1963).

(18) Hagenguth, J. H., et al., "Lightning to the Empire State Building", Part III, AIEE Transactions, p 649 (August 1952).

(19) Shaeffer, J. F., "Aircraft Initiation of Lightning", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 192.

(20) Ibbott, J. D., "The Effect of Lightning on Materials", Aircraft Engineering, p 25 (April 1972).

(21) Dawson, G. A., "Ice Crystal Electrification", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 18.

(22) Tanner, R. L., "Precipitation Charging and Corona-Generated Interference in Aircraft", AFCRL 336, Technieal Report No. 73, Stanford Research Institute, Menlo Park, California, Contract No. AF19 (604)-3458, SRI Project No. 2494 (April 1961).

(23) Schmitt, Jr., "Conductive Polymeric Coatings for Combined Anti-Static Properties and Erosion Resistance", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 88.

(24) Bachman, K. C., et al., "Tank Truck Incidents Attributed to Static Electricity, 1960-1969", Report No. RL-72M-69, Esso Research and Engineering Co., Linden, New Jersey (September 1969).

(25) Bachman, K. C., et al., "Aircraft Incidents Attributed to Static Electricity, 1959-1969", Report No. RL-45M-69, Esso Research and Engineering Co., Linden, New Jersey (July 1969).

(26) Leonard, J. T., "Principals of Electrostatics in Aircraft Fuel Systems", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 192.

(27) Nanevicz, J. E., "Results of Titan III Flight Electrostatic Experiments", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 1[illegible]6.

(28) Amman, E. A., "The Problem of Lightning and Static Electricity at the Kennedy Space Center", 1970 Lightning and Static Electricity Conference (December 1970), p 321.

(29) Cianos, N., "Structure of Lightning Noise", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 50.

(30) Solak, B. J., "Helicopter Cargo Handling - Electrostatic Considerations", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 579.

(31) Buser, R. G., et al., "Aerosol Discharge System for Heavy Lift Helicopters", Report No. AFAL-TR-72-325, 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 622.

(32) Amason, M. P., et al., "Lightning Current Transfer Characteristics of the P-Static Discharger Installations", 1970 Lightning and Static Electricity Conference (December 1970), p 99.

(33) Horeff, T. G., "FAA DC-9 Liquid Nitrogen Fuel Tank Inertive Program", Second Conference on Fuel System Fire Safety, FAA, Washington, D. C. (May 1970), p 193.

(34) Clodfelter, R. G., "Fuel Tank Inerting Using Catalytic Combustion Techniques", Second Conference on Fuel System Fire Safety, FAA, Washington, D. C. (May 1970), p 141.

(35) Letter from Ogston, A. R., Aviation Week and Space Technology (December 4, 1972), p 62.

(36) Newman, M. M., "Lightning Discharge Channel Characteristics", in Recent Advances in Atmospheric Electricity, edited by L. G. Smith, Pergamon Press, New York, (1958).

(37) Brook, M., et al., "Artificial Initiation of Lightning Discharges", Journal of Geophysical Research, Vol 66, pp 3967-3969 (November 1961).

(38) Young, G. A., "A Lightning Strike of an Underwater Explosion Plume", Report No. 61-43, U.S. Naval Ordnance Laboratory (1961).

(39) Fitzgerald, D. R., "Aircraft and Rocket Triggered Natural Lightning Discharges", 1970 Lightning and Static Electricity Conference, sponsored jointly by Air Force Avionics Laboratory and Society of Automotive Engineers (December 1970), pp 3-9.

(40) Personal Communication with Claud Austin, Wright-Patterson Air Force Base, Ohio (April 1972).

(41) Brook, M., et al., "Artificial Initiation of Lightning Discharges", Journal of Geophysical Research, Vol 66, No. 11, p 3967 (November 1961).

(42) Personal interview with Dr. Barnard Vonnegut, Professor at State University of New York, Albany (May 23, 1972).

(43) Personal interview with Professor C. B. Moore, New Mexico Institute of Mining and Technology, Langmuir Laboratory, Socorro, New Mexico (June 26, 1972).

(44) Pierce, E. T., oral statement made during discussion of paper presented at 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972).

(45) Hodkinson, J., "A Lightning Discharge to a Balloon at Cardington", Meterological Magazine (Great Britain), Vol 91, No. 1081, p 230 (August 1962).

(46) Stahmann, J. R., and Robb, J. D., "Lightning Protection for Tethered Balloon With Power Cable", Final Report, Lightning and Transients Research Institute, Miami Beach, Florida, Contract No. F8606-69-C-0030, prepared for Air Force Eastern Test Range, Patrick Air Force Base, Florida (April 1969).

(47) Quinliran, J., "New Developments in Lightning Protective Coatings for Advanced Structural Composites", Report No. AFAL-TR-72-325. 1972 Lightning and Static Electricity Conference, Las Vegas, Nevada (December 1972), p 315.

(48) Stahmann, J. R., "Lightning Stroke to a Tethered Balloon Cable", Investigative Report, Lightning and Transients Research Institute, Miami Beach, Florida, prepared for Air Force Eastern Test Range, Patrick Air Force Base, Florida (August 19, 1972).

(49) Golden, R. L., "Atmospheric Electricity and Tethered Balloons", prepared for Schjeldahl Co. (March 10, 1969).

(50) Appleman, H. S., "Lightning Hazard to Aircraft", Technical Report No. 199, Headquarters, Air Weather Service (MAC), U. S. Air Force (April 1971).

(51) Harrison, L. P., "Lightning Discharges to Aircraft and Associated Meterological Conditions", NACA Technical Note No. 1001 (May 1946).

(52) Schonland, B. F. J., The Flight of Thunderbolts, Oxford University Press (1964).

(53) Müller-Hillebrand, D., "Beeinflussung der Blitzbahn durch radioaktive Strahlen und durch Raumladungen", Electrotechnische Zeitschrift, A, Vol 83, p 152 (1962).

(54) British Standards Institution, The Protection of Structures Against Lightning, London (1965).

(55) Etherington, H. (Editor), Nuclear Engineering Handbook, McGraw-Hill, New York (1958).

(56) Koopman, D. W., and Wilkerson, T. D., "Channeling of an Ionizing Electrical Streamer by a Laser Beam", Journal of Applied Physics, Vol 42, No. 5, p 1883 (April 1971).

(57) Hagen, W. F., "Diffraction Limited High-Radiance Nd Glass Laser System", Journal of Applied Physics, Vol 40, No. 2, p 511 (February 1969).

(58) Telephone conversation between D. Applebaum of Battelle's Columbus Laboratories and D. W. Koopman of Versar, Incorporated (March 1973).

(59) Loeb, L. B., "Confirmation and Extension of a Proposed Mechanism of the Stepped Leader Lightning Stroke", Journal of Geophysical Research, Vol 73, No. 18, pp 5813-5817 (September 1968).

(60) Pendleton, W. K., et al., "Investigation of a Laser Triggered Spark Gap", Review of Scientific Instruments", Vol 36, No. 11, p 1546 (November 1965).

(61) Kleme, R. C., "Space-Charge Injection: A New Technique for Studying Non-Uniform Field Breakdown Phenomena", Applied Physics Letters, Vol 15, No. 6, p 155 (September 15, 1969).

APPENDIX A

LIGHTNING PROTECTION OF AIRCRAFT VIA PROPER FLIGHT PLAN

The report of the NACA Subcommittee on Lightning Hazards to Aircraft[51], provided one of the first comprehensive summaries of lightning strikes to aircraft. This report was based on approximately 170 reports over all seasons for the period 1935 to 1944. During this period the majority of the flying was done with nonpressurized airplanes operating below 15,000 ft and without the use of radar. Figure A-1 depicts the frequency of strikes as a function of altitude above the ground. The majority of lightning strikes (approximately 75 percent) occurred between 1,000 and 2,700 m (3,000 and 9,000 ft). Only four hits were received by aircraft below 1,000 (ft), and one of these aircraft was on the ground.

Now, the question is whether the peak frequency of strikes near 2,100 m (7,000 ft) has a physical basis or is merely a reflection of the altitude of maximum traffic. To check this question, Appleman[50] studied reports of lightning strikes to military aircraft during the period January 1961 to July 1964. These data included 20 reports from propeller aircraft, 20 from jets, and 8 from propjets. The data were analyzed in terms of frequency of lightning strikes as a function of altitude (MSL) (see Table A-1).

TABLE A-1. FREQUENCY OF LIGHTNING STRIKES TO PROPELLER, PROP-JET, AND JET AIRCRAFT AS A FUNCTION OF ALTITUDE FOR THE PERIOD JANUARY 1961 TO JULY 1964

Altitude Range, 1,000 ft	Number of Cases
0-5	7
5-10	21
10-15	9
15-20	8
>20	3

82

~~A-2~~

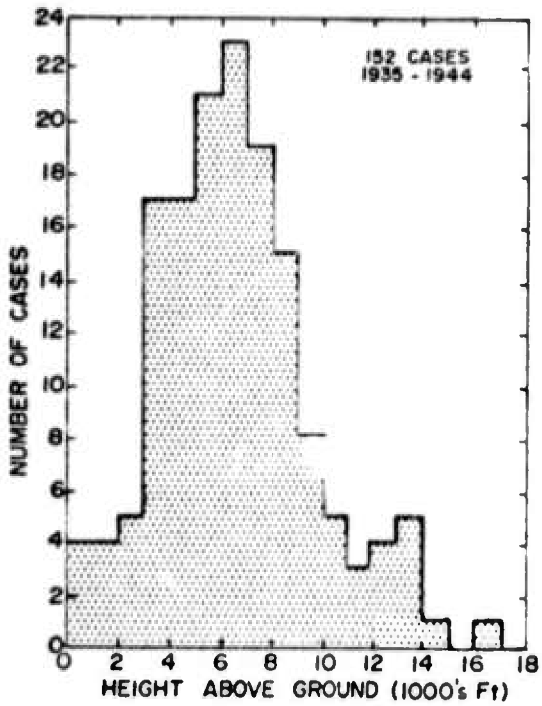

FIGURE A-1. NUMBER OF LIGHTNING STRIKES TO AIRCRAFT AS A FUNCTION OF HEIGHT ABOVE GROUND

From Reference 51.

Although the flight altitudes averaged much higher for this later study, the level or peak frequency of hits was similar to that of the study made 25 years before. Recall that just 20 strikes of jet aircraft were considered, and it was found that 15 occurred under 4,600 m (15,000 ft), far below jet cruising altitudes. Only two hits were recorded by Appleman as being received above 9,100 m (30,000 ft) and none above 10,600 m (35,000 ft). Appleman concluded that the "obvious" reason for the majority of strikes occurring at the lower altitudes must in a large part be related to inherent physical properties of the thunderstorm, and not merely to the altitude of maximum traffic.

The NACA study[51] also included the ambient flight-level temperature of the lightning-strike occurrences in addition to the altitude. Figure A-2 shows the strike frequency as a function of temperature. Referring to Figure A-2, we can see that the majority of hits were received between ±5 C. To exhibit these three variables (hit frequency, ambient temperature, and altitude) in one representation, Appleman plotted occurrence of lightning strokes as a function of temperature and altitude using data from the NACA study (Figure A-3).

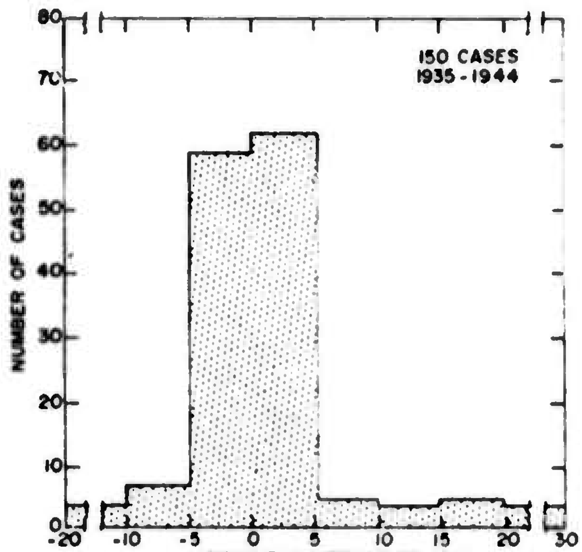

FIGURE A-2. NUMBER OF LIGHTNING STRIKES TO AIRCRAFT AS A FUNCTION OF AMBIENT TEMPERATURE

From Reference 50.

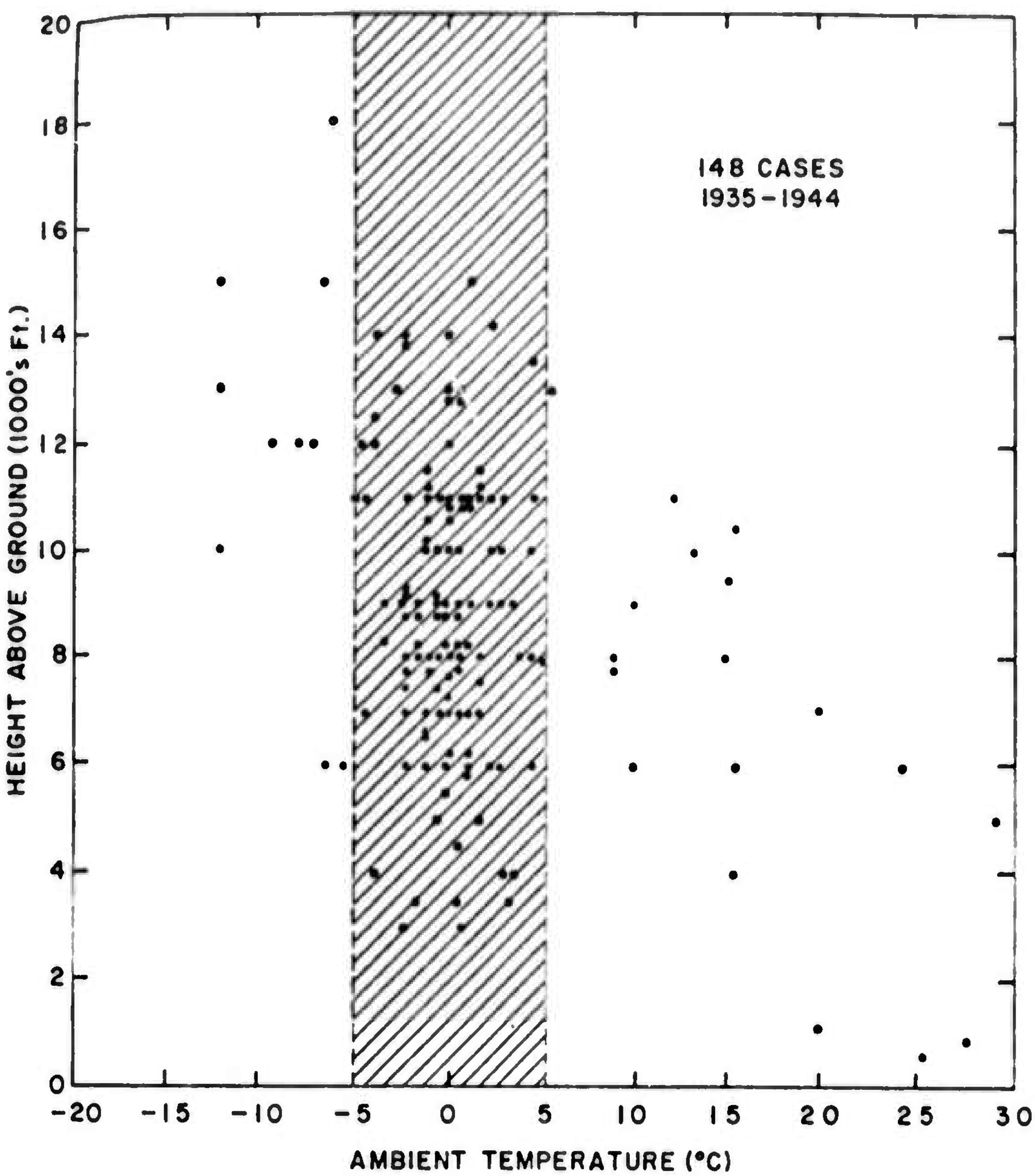

FIGURE A-3. OCCURRENCE OF LIGHTNING STRIKES AS A FUNCTION OF TEMPERATURE AND ALTITUDE

From Reference 50.

APPENDIX B

A SIMPLIFIED ANALYSIS OF A POSSIBLE LASER-GUIDED MECHANISM FOR STEPPED LEADERS

Although the situation of lightning discharge is, in the strictest sense, dynamic, it is useful to employ the simplification of the static approximation. In this approximation the conductivity and associated terms will be assumed to be time independent during the initial stages of the formation of a lightning stroke.

Consider the stepped leader. To a first approximation this is a negative charge of magnitude, Q. The force of attraction between Q and the earth is:

$$\bar{F} = -Q\bar{E} \quad ,$$

where

$$\bar{E} = -\bar{\nabla}\phi \quad ,$$

and

$$\phi = -Q(4\pi\varepsilon r)^{-1} \quad .$$

It follows that where the potential gradient, $\bar{\nabla}\phi$, is the highest, the leader will tend to go. The dielectric constant, ε, is one key to control for it is related to the conductivity and index of refraction. So, for our purposes we will consider ε as a function of the geometry. For simplicity let us concern ourselves with the $x\hat{\imath}$ direction in an orthogonal rectangular coordinant system where $z\hat{k}$ is normal to the earth's surface. Then $\bar{\nabla} \rightarrow \hat{\imath}\,\frac{\partial}{\partial x}$, and the potential gradient becomes:

$$\hat{\imath}\,\frac{\partial \phi}{\partial x} = \frac{-Q}{4\pi}\,\hat{\imath}\,\frac{\partial}{\partial x}\left(\frac{1}{\varepsilon(x)} \cdot \frac{1}{x}\right)$$

$$= \frac{-Q}{4\pi}\,\hat{\imath}\left(\frac{1}{\varepsilon(x)} \cdot \frac{\partial}{\partial x}\left(\frac{1}{x}\right) + \frac{1}{x} \cdot \frac{\partial}{\partial x}\left(\frac{1}{\varepsilon(x)}\right)\right)$$

$$= \hat{\imath}\,\frac{Q}{4\pi x\varepsilon(x)}\left(\frac{1}{x} + \frac{1}{\varepsilon(x)} \cdot \frac{\partial \varepsilon(x)}{\partial x}\right) \quad .$$

Let us now artificially modify the dielectric term so that

$$\varepsilon(x) = \varepsilon_{amb}(x) + \varepsilon_{ind}(x)$$

where $\varepsilon_{amb}(x)$ is the ambient or natural dielectric term and $\varepsilon_{ind}(x)$ is the induced dielectric term we hope to control. One has:

$$\hat{\imath}\,\frac{\partial\phi}{\partial x} = \frac{\hat{\imath}\,Q}{4\pi x(\varepsilon_{amb}(x) + \varepsilon_{ind}(x))}\left(\frac{1}{x} + \frac{1}{(\varepsilon_{amb}(x) + \varepsilon_{ind}(x))}\cdot\frac{\partial(\varepsilon_{amb}(x) + \varepsilon_{ind}(x))}{\partial x}\right)$$

Clearly, $\varepsilon_{amb}(x)$ does have a slight dependence on the geometry which would then account for the irregular path observed for the stepped leader. However, we assume this spatial dependence to be a small part of ε_{amb}. Making the usual assumption then

$$\varepsilon_{amb} \simeq \varepsilon_o \equiv \text{constant}$$

and

$$\hat{\imath}\,\frac{\partial\phi}{\partial x} = \frac{\hat{\imath}\,Q}{4\pi x(\varepsilon_o + \varepsilon(x))}\cdot\left[\frac{1}{x} + \frac{1}{\varepsilon_o + \varepsilon(x)}\cdot\frac{\partial\varepsilon(x)}{\partial x}\right]$$

where the "ind" subscript is to be understood for $\varepsilon(x)$.
We would like to arrange things to have

$$\frac{1}{\varepsilon_o + \varepsilon(x)}\cdot\frac{\partial\varepsilon(x)}{\partial x} >> \frac{1}{x}$$

and, if we recall that these are vector quantities representative of all the coordinate terms, then this condition is a statement of direction as well as magnitude and is formally equivalent to attempting to maximize $\bar{\nabla}\varepsilon$ in planes parallel to the earth's surface. Without elaboration we note that

$$\bar{\nabla}\varepsilon = \bar{\nabla}\left(1 - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega}\right)$$

where

ω = the frequency of the laser emission

ω_p = plasma frequency

Γ = classical Coulombic damping constant

$\bar{\nabla}\omega_p^2 = \frac{4\pi e^2}{m}\,\bar{\nabla} N_e$

N_e = the electron density

We note that, at least in this simple examination, it is not N_e that must be maximized but the <u>space gradient</u> of the electron density, $\bar{\nabla}N_e$. Hence, a minimum production of free electrons within a collimated laser beam may be sufficient to fulfill this requirement, possibly below laser intensities sufficient to cause optical breakdown of the air.